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MODELING MARINE EXPOSURE TO POLYCHLORINATED BIPHENYLS FROM SUNKEN SHIPS

THESIS

Charles N. Wendt, Captain, USAF

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The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

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Presented to the Faculty of the Graduate School of Engineering

Air Education and Training Command

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Engineering and Environmental Management

Charles N. Wendt, B.S.

Captain, USAF

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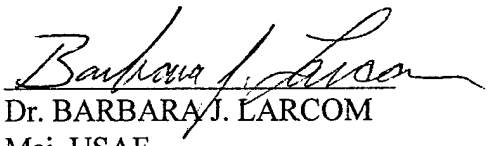
Dr. CHARLES A. BLECKMANN



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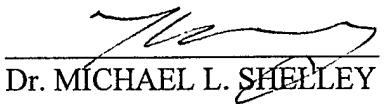


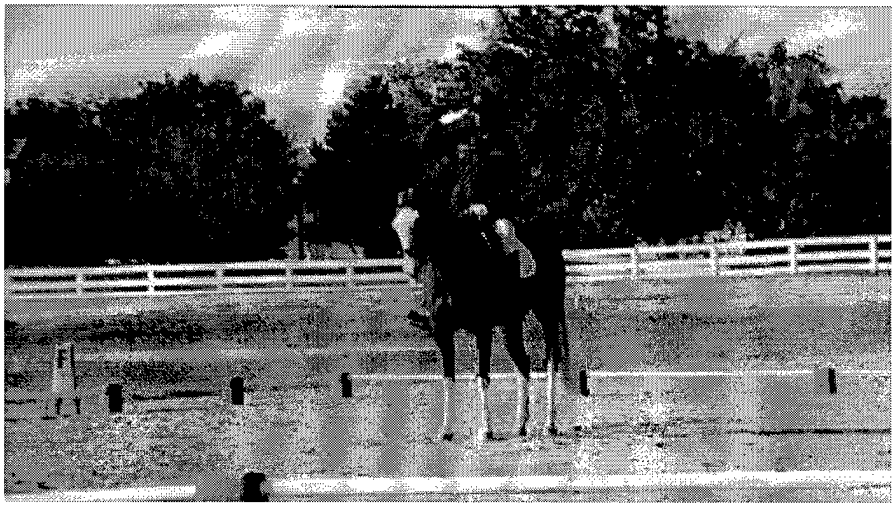
Dr. MICHAEL L. SHELLEY
Lt Col, USAF

Acknowledgments

For a horse named "Skip." When the weight of the world was on my shoulders, he still carried me faithfully and tirelessly on his.

And for riding coach and now fiancée, Ms. Kelley Anne McCarty, who understands that an officer's duty is no longer conducted on horseback.

Finally, to my committee of LtC Dr. Michael L. Shelley, Dr. Charles A. Bleckmann, and Maj Dr. Barbara J. Larcom who set aside their time so that I could have the opportunity of rising to the thesis challenge.



Representing the USAF, Captain Charles N. Wendt
and "Skip" begin their dressage test.
Jump Start Horse Trials
Kentucky Horse Park, Lexington, Kentucky
5-6 October 1996

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Abstract

In the past, the U.S. Navy has routinely conducted SINKing EXercises (SINKEX) for training, weapon effectiveness tests, and economic disposal of aging assets. Recent concern over polychlorinated biphenyl (PCB) chemicals aboard such target vessels has resulted in a suspension of SINKEX. The U.S. Navy has approximately 200 vessels currently requiring such disposal. Environmental legislation and health concerns preclude selling such vessels to foreign governments or scrapping.

This work attempted to model the fate and transport of these PCBs by examining their transport to coastal water and their accumulation in the marine food chain. The model includes biodegradation, upwelling, partitioning of PCBs to sediment, sediment transport, bioaccumulation, biomagnification, and biological migration. Seasonal fluctuations in marine biomass and storm activity and how this affects PCB concentrations is also examined. The model uses a four trophic level approach for the marine food chain. A total of 55 runs, each simulating a 50 year period, were conducted.

Model output and subsequent sensitivity analysis of parameters indicate that the potential for adverse impact to the marine ecosystem is minimal.

I. Introduction

Background

Barring accidents and wartime losses, retired United States Navy vessels have been sunk for three primary reasons: training, weapon tests, and disposal. In the past, SINKing EXercises (SINKEX) evaluated weapon systems and provided realistic training to sailors and aviators. Air-to-surface and/or surface-to-surface weapon systems are fired at the target ship. Such exercises only utilize conventional explosives in weapon warheads. The old ship simulates a potential threat and provides a realistic target for conventional ordnance, weapon systems, and tactics employed (Department of the Navy, 1971:1). Obsolete warships are ideal targets for evaluating the effectiveness of conventional weapons in the development of new and better weapon employment tactics. It is difficult to recreate inherent characteristics such as water-tight integrity and hull profile in simulated warships (Department of the Navy, 1971:2). These platforms are older vessels that have outlived their usefulness or are too expensive to maintain. Many were built in the 1940's during World War II and are mothballed in the inactive reserve. There is concern that the polychlorinated biphenyl (PCB) chemicals on board SINKEX ships will cause environmental damage.

Research Statement

This work attempts to model the fate and transport of these PCBs in the marine ecosystem. As these materials are released from the site, they will be absorbed by various

plant and animal species. The research effort will not attempt to ascertain the effect of this absorption, but rather to model how much material will reside in each trophic level. Samples scheduled to be taken from a site off the coast of San Diego can be used for model validation when the data becomes available.

In the past, SINKEX has caused little objection. Hulls are cleaned before use and provide a protective area for smaller marine life similar to coral reefs. The corrosive sea water and the continual stress of currents will eventually degrade the wreck (Department of the Navy, 1971:6). However, the more recent discovery of PCB containing materials aboard these vessels has caused great concern in regards to negatively impacting the marine ecosystem. Currently, the Navy is actively seeking to reduce its inventory of old vessels by as many as 200. The majority of these are submarines, which alone cost nearly $1 billion annually for removal of PCB contaminated materials (Operational Technologies Corporation, 1995:1-2)

Legislation

In order for a SINKEX to be approved, the site must take place 50 nautical miles from the nearest land, be clear of the shipping lanes, and have a water depth of at least 6000 feet. A general permit issued under the terms of the Marine Protection, Research and Sanctuaries Act (MPRSA) of 1972 by the Environmental Protection Agency (EPA) drives specific requirements. This also requires removing to the maximum extent practicable of materials which may damage the marine environment (Captain T.N. Ledvina, USN, JAGC, 1995:1). PCBs are the main concern because such chemicals are highly persistent. They biomagnify in

food chains and can reach high concentrations in birds and mammals (Richter and others, 1994:3). Several mixtures of PCBs have caused cancer in laboratory animals and they are considered by the Ocupational Safety and Health Agency and the National Institute of Occupational Safety and Health to be suspected human carcinogens (Operational Technologies Corporation, 1995:9).

PCBs were not specified to be used in building materials, but rather were used by vendors to meet military specifications regarding fire retardance and lack of electrical conductivity (Richter and others, 1994:3). As such, PCB containing materials can be readily found in sound dampening felt, paints, mastic, cork insulation, gaskets, electrical cables, transformers, and ventilation duct insulation in considerable concentrations (Operational Technologies Corporation, 1995:9). Ventilation duct flanges of wool felt and rubber gasket materials consist of PCBs at varying concentrations of up to 500,000 ppm (Hood, 1995). Insulation jackets protecting electrical cable have up to 500 ppm PCBs (Hood, 1995). Most electrical equipment and POL products can be readily removed before sinking, but others are not feasible to access. Transformers can be drained of fluid and taken off for disposal. Gaskets and duct flanges, however, number in the thousands and electrical cable runs for miles. These items couldn't be completely removed short of dismantling the entire ship (Dooley). The removal of PCB containing petroleum, oil, and lubricants is readily accomplished by flushing the tanks and is not a significant factor. Special cleaning, preparation, and inspection are conducted to determine that hulls have been defueled and that all tanks and lines are, in essence, free of petroleum (Department of the Navy, 1971:2-3). Still, extraction of the readily removable components could still leave in the worst case the

equivalent of 100 lb. of pure PCBs on board when the ship is sunk (Richter and others, 1994:2). The EPA defined regulatory threshold currently is 50 ppm in any PCB containing material (Operational Technologies Corporation, 1995:3).

Alternatives to sinking at sea are exporting to foreign governments or scrapping. The Toxic Substances Control Act (TSCA) regulations discussed below make selling illegal. Scrapping makes the Navy financially liable for the health and safety of the scrapping personnel. Personal protection gear would need to be worn to protect workers from PCBs. Cutting operations would generate dioxin and chloro-furans through pyrolytic reactions. These chemicals are very toxic byproducts of PCBs and high temperatures (Operational Technologies Corporation, 1995:i). This would make scrapping a hazardous as well as expensive option. Sinking at sea with the benefit of providing realistic training appears an attractive alternative for disposal of these vessels. Without real targets to use, the Navy must construct them at considerable expense.

The use of obsolete vessels for SINKEX was stopped in September 1994 by the EPA (Captain T.N. Ledvina, USN, JAGC, 1995:1). It is argued that such a sinking constituted an export for disposal of PCB chemicals in excess of 50 ppm. This would violate TSCA which only authorizes the import and export of PCBs for disposal in concentrations less than 50 ppm (Operational Technologies Corporation, 1995:17). Pending legislation introduced by the EPA in December 1994 may be even more restrictive. This would impact disposal, manufacturing, processing or distributing PCBs or PCB items including commodities, byproducts, sediments, spoils and contaminated materials (Operational Technologies Corporation, 1995:1). The U.S. Navy disagrees. Since the ship remains the property of the United States of America, it

doesn't constitute an export or disposal. The EPA prohibition on export does not apply as there is no distribution for commercial purposes (Captain T.N. Ledvina, USN, JAGC, 1995:2). In addition, a computer simulation model conducted by the Navy concluded that if the amount of PCBs aboard sunken ships in a releasable form does not exceed 30 pounds for a small ship or 100 pounds for a large ship it will have no significant effect on the marine environment. These figures are based upon laboratory release rates and expert's intuition of PCB fate in the marine environment and not on any empirical data (Sterner, 1994:4). In short, the point is being argued on both legal and ecological bases.

The two major pieces of legislation governing PCBs at sea are the Toxic Substances Control Act and the Ocean Dumping Act. In 1976, the EPA adopted regulations that governed the use, control, and disposal of PCBs. Included are provisions for reporting spills and how to clean them up. The two acceptable methods for disposal are land burial and incineration. Dumping at sea is not allowed (Sterner, 1994:2). The Marine Protection Research and Sanctuaries Act of 1972 (the Ocean Dumping Act) bears on the U.S. Navy in two ways. First, disposal of waste at sea is prohibited without a permit. The Navy has permits for the intentional sinking of ships for disposal purposes as well as one for SINKEX (Sterner, 1994:2). The permits require that all but trace amounts of PCBs be removed in accordance with the international guidelines under the London Dumping Convention. Trace amounts are those with no significant biological effects and for typical circumstances is considered to be 50 parts per billion (ppb) in the PCB containing media (Sterner, 1994:3).

Resolution of legislative conflicts will be the result of discussion between the lawyers of the EPA and the Judge Advocate General (JAG). An input to such discussion is scientific

study. The true ecological impact of SINKEX must be determined to make wise decisions governing realistic training and economic disposal of aging assets. A model designed by the Environmental Sciences Division of Naval Command Control and Ocean Surveillance Center was constructed to predict possible ecological effects of SINKEX (Richter and others, 1994). Samples are scheduled to be drawn from sites off the coast of San Diego where previous SINKEXs were conducted in an effort to validate this model.

Problem Scope

In the original model, transport mechanisms to the shallow water ecosystem were neglected. It was argued that PCBs in the deep benthic environment have little or no chance of physical or biological transport to surface waters (Richter and others, 1994:2). However, a physical marine transport process called "upwelling" routinely moves materials from the depths to the photic zone which is shallow enough for light to penetrate (Barnes and Hughes, 1988:11; Smith, 1992:10-11; Dorman and Palmer, 1980:55). The purpose of my thesis is to evaluate that pathway which consists of three transport mechanisms: current, sediment, and biological. Although PCBs are generally hydrophobic and do not readily dissolve in water, the shear volume of water involved is capable of delivering a great amount of PCB materials. Such wave action will also move sediments which PCB materials readily adhere to into the shallow water ecosystem. Finally, marine life that has absorbed PCB chemicals through biomagnification and bioaccumulation may move PCBs by migration.

For purposes of this model, the marine ecosystem consists of all living things that live in or venture into the ocean (including birds, otters, and sea-lions) and their interaction with

their non-living surroundings. The model portrays this system as a series of reservoirs that contain PCBs and attempts to define the rate of transfer from one reservoir to another. For example, PCBs may be introduced into the ocean water from the wreck, and then absorbed by plants which are eaten by fish. These fish will be eaten by a large predator such as a shark which later dies to return the PCBs back to the water. While initially all PCB material will be at the site, it will be removed great distances by numerous cycles similar to the example above. The effect of so much PCB material in a particular compartment of the model is left to a future toxicology study.

Research Questions

The effort seeks answers to the following questions: Is there a potential for PCB biomagnification in the food chain? Is experimentation necessary to closely determine partition coefficients? Are migration rates of organisms important in the behavior of the system? Does biodegradation by microorganisms play a role in determining accumulation by higher marine organisms?

II. Literature Review

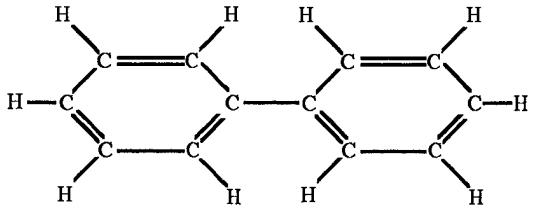
To better comprehend this research effort, it is necessary to have some understanding of the scientific processes involved. Addressed in this chapter is a discussion of what PCBs are and their behavior in the marine environment, how bacteria break down PCBs into non PCB materials which are not of concern, and transport processes that will remove PCBs from the wreck to the shallow water ecosystem. The marine ecosystem itself will also be discussed and how organisms uptake PCBs. Finally, the U.S. Navy's original model is described.

Polychlorinated Biphenyls

Polychlorinated biphenyls are a subclass of synthetic substances called chlorinated organic compounds and consist of chlorine, carbon, and hydrogen atoms. PCB compounds are either thick oily liquids or sticky brittle gum ranging in color from light amber to black. Such chemicals are relatively fire resistant, don't conduct electricity, have low volatility at normal temperatures, and don't readily react with other compounds. These properties were desirable in a large number of industrial applications including electrical equipment, hydraulic fluid, sealants, felt insulation for ductwork, flame retardant paints, and other uses. Although first manufactured in 1881, wide scale production did not occur until 1929. They were sold under various trade names such as Aroclor, Pyranol, Interteen, and Hyvol with production termination in North America in 1977 (FAQ's, 1996). Until the discovery of biodegradation, the only known way to destroy such compounds was to expose them to over 1100 degrees Celsius heat or, in the presence of certain chemical agents, lesser heat (FAQ's, 1996).

In the late 1960's, PCBs were discovered in birds residing in Sweden. The poisoning of 1200 people in Japan by rice oil during the same time period brought public attention to the potential dangers of this class of chemicals. By 1972 there was scientific evidence that PCBs were a serious hazard to both humans and the environment. All such compounds have now been functionally replaced by newer and safer chemicals, but the large amount of PCBs produced and their toxicity and persistence give rise to concerns of their fate and transport in the environment (FAQ's, 1996). Coupled with their tendency to accumulate in biota, the environmental fate of PCBs is very important (Bedard and May, 1996:237). PCBs are generally considered highly persistent in soils, sediments, and other natural environments (Quensen III. and others, 1988:752). This allows for the chemicals to be conveyed over great distances through the food chain, or by natural transport mechanisms such as tidal action or groundwater.

PCBs consist of chlorine atoms bonded to two phenyl rings. The biphenyl molecule portrayed in Figure 1 provides up to 10 sites for various chlorines to bond. The ten different bonding sites create a class of chemical which consists of 209 different congeners, or other compounds within the PCB class. Congener 0 is the biphenyl molecule and congener 209 is decachlorobiphenyl with all bonding sites occupied by chlorine atoms. Most congeners are present, in differing proportions, in commercial PCB mixtures.



Biphenyl Molecule

(Any and all Hydrogen molecules, represented by H, could each be replaced by a single Chlorine molecule. This would formulate one of the 209 theoretically possible PCB congeners.)

Figure 1

Commercial PCB mixtures were fairly consistent from batch to batch, but analysis is very difficult because of the large number of different congeners. The congeners all have different chemical properties with regards to vapor pressure, solubility, etc., but the specifics are not well documented as very few of the congeners have been produced in sufficient quantities to analyze individually. Because of this, it is necessary to draw generalities and utilize average values for physical properties such as partition coefficients and solubility (Richter and others, 1994:5). This has been documented by grouping congeners with other congeners which have a like number of chlorine atoms on each molecule.

Laboratory experiments showed that solubility of PCBs in artificial sea water is approximately five times lower than in distilled water. Values for distilled water at room temperature as parts by weight range from 5.9 ppm for monochlorinated, 0.3 ppm for dichlorinated, 6 ppb for heptachlorinated, and 15 ppb for decachlorinated biphenyl congeners (Richter and others, 1994:5). Different isomers have different properties, but the values are accepted within 10% error of any given congener of a particular class (Richter and others, 1994:5).

In general, the PCB congeners are relatively insoluble in water and have low vapor pressures. These characteristics result in high lipid partition coefficients, causing accumulation in lipid tissues and biomagnification in the food chain (Abramowicz and Olson, 1995:36). PCBs have very high octanol/water partition coefficients ranging from 10^5 to 10^7 (Richter and others, 1994:6). This is thought to increase with increasing chlorination (Bright and others, 1996:2504). Because of their suspected carcinogenicity, biomagnification is of great concern.

Sediment/water coefficients are from 10^3 to 10^4 which indicates a tendency to adsorb onto sediments. Partitioning is relatively rapid. Experiments in many cases showed equilibrium with sediment/water to be reached in a matter of hours (Richter and others, 1994:6). Core samples from lakes and rivers indicate the majority of PCBs reside in the organic phase of the sediment. Researchers expected this result because in natural systems hydrophobic compounds partition to organic matter. Many of the lowest organisms of the food chain are located in the sediments (Harkness and others, 1993:505). Organic carbon does not affect absorption onto the sediments to any appreciable extent. According to Provini, PCBs are kept in the top layer of the sediment by their lipophilicity and the freshly settled biomass there (Provini, 1995:131-132). This conflicts, however, with other research which maintains that organic carbon remains an important parameter in absorption to sediments (Ernst, 1990:83).

Biodegradation

Until relatively recent years, the scientific community thought that polychlorinated biphenyls did not degrade in the environment. Fueling this belief are the intermediate byproducts of PCB breakdown, which were in turn also PCB chemicals. When sold under the trade name Aroclor, the non-homogenous PCB mixture was expressed with a number, 12XX. The first number, "12" referred to the number of carbon atoms in the molecule. The "XX" denoted the percent of the mixture's weight that resulted from the chlorine atoms. As these molecules lost chlorine atoms through biodegradation, the average weight of chlorine in the mixture fell. Total degradation was never reached because chlorinated PCBs were replaced with new PCB pollution. Analysts routinely reported PCB concentrations in terms of whichever commercial Aroclor approximated the same average chlorine level to match their samples. When samples were taken, the lower chlorine weight sample was misidentified as a different, and less heavily chlorinated, commercial PCB mixture than originally introduced to the system. This data recording practice lead to severe qualitative errors in the mass of PCBs involved. Chemicals that were originally heavily chlorinated and had undergone anaerobic degradation were thus mistaken for other common PCB chemicals. This mistake hid evidence and delayed realization of PCB degradation for many years as well as concealing the diversity of the involved microbiological processes (Brown and others, 236:711).

Samples from the Hudson river do show that PCBs are being biodegraded in the environment. In cultures under anaerobic conditions, analogous position-selective dechlorination of chlorobenzoates and chlorophenols occurred. Such processes stopped when

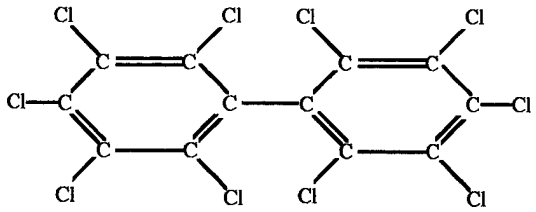
the samples were sterilized. This indicates that microorganisms are responsible for the dechlorination (Brown and others, 236:711).

Microorganisms degrade PCBs through two different mechanisms: anaerobic and aerobic. In the absence of oxygen, anaerobic bacteria remove chlorine atoms from the biphenyl molecule and replace them with hydrogen atoms. This process does no damage to the carbon-carbon bonds of the biphenyl rings (Harkness and others, 1993:503). The result is lower chlorinated congeners (Beurskens and others, 1995:939). Aerobic bacteria break apart the dechlorinated and lesser chlorinated biphenyl rings into their respective chlorobenzoic acids through oxidative destruction (Abramowicz and Olson, 1995:36). At this point they are no longer PCBs and react in the water to eventually break down into common organic substances.

The ocean floor sediments are an anaerobic environment where PCBs collect due to their partition coefficients. Environmental surveys show PCB dechlorination is prevalent in many marine and aquatic sediments (Abramowicz and Olson, 1995:38). Anaerobic biological and chemical processes often dominate flooded sediments (Haluska and others, 1995:327). Concentrations of PCBs and chlorinated benzenes in sediments are substantially reduced by anaerobic microbial processes through complete dechlorination (Beurskens and others, 1995:939). Reductive dechlorination processes are significant because they are believed to make the PCB compounds both less toxic and less persistent (Bedard and May, 1995:237).

Not all chlorines are attacked by the anaerobic organisms equally. Laboratory evidence shows that certain chlorines are removed before others. This is best demonstrated with decachlorobiphenyl which has all chlorines and no hydrogen atoms at the ten bonding

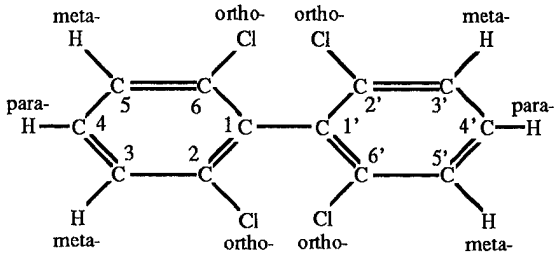
sites. Thus, decachlorobiphenyl has no chlorine-free sites for aerobic attack. The elimination of this congener most probably results from reductive dechlorination (Haluska and others, 1995:329). Its molecular diagram is displayed as Figure 2.



Decachlorobiphenyl

Figure 2

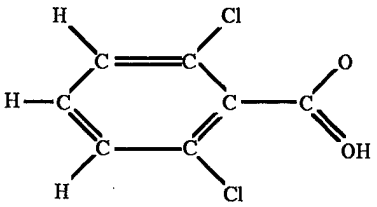
In a dechlorination experiment of the decachlorobiphenyl molecule over a 40 day incubation, data shows that 10.6% of the total chlorine and 7.5% of *ortho* chlorine was removed. This suggests that *meta* and *para* chlorines are removed preferentially. These *meta* and *para* chlorines are generally associated with the toxicity of the PCB molecule (Haluska and others, 1995:329). Anaerobic removal of *meta* and *para* chlorines converts highly chlorinated PCB congeners to lower chlorinated, *ortho* substituted congeners through reductive dechlorination (Abramowicz and Olson, 1995:37). There is some evidence of *ortho* chlorines being removed anaerobically, but it is a minor process (Berkaw and others, 1996: 2537-2538). The conclusion of decachlorobiphenyl's anaerobic degradation is given in Figure 3.



2,6,2',6' Tetrachlorobiphenyl

Figure 3

As previously stated, a wide range of aerobic organisms can attack the phenyl rings and convert the compound into its corresponding chlorobenzoic acid. Although the more lightly chlorinated congeners are preferentially degraded, a wide variety of PCBs can be broken down in this manner. PCB congeners are converted into their corresponding chlorobenzoic acids through the 2,3 Dioxygenase metabolic pathway. Such chlorobenzoic acids are readily degraded by native bacteria. Byproducts are carbon dioxide, water, chloride, and biomass (Abramowicz and Olson, 1995:37). The chlorobenzoic acid associated with the aerobic degradation of 2,6,2',6' Tetrachlorobiphenyl is given by 2,6 Dichlorobenzoic acid shown in Figure 4.



2,6 Dichlorobenzoic acid

Figure 4

The number of indigenous biphenyl-metabolizing microorganisms that were measured in aqueous samples by plate counts increased by at least six orders of magnitude when provided with O_2 ,other nutrients, and biphenyls (Harkness and others, 1993:504).

Recent research has demonstrated the biodegradation of PCBs in the environment. Although the degradation rate in the field is only a third as fast as the laboratory, samples demonstrate a field biodegradation rate of 0.09 to 0.48 mg of PCBs per Kg of PCBs per day (Harkness and others, 1993:505). This rate is very slow by itself. When bacteria can't degrade such materials because they are residing in the lipids of marine organisms, residence time in the world's oceans is considerable.

Exercise Area

Off the coast of San Diego, California, is the site of numerous SINKEXs (Groff, 1975:2; Sterner, 1994:9). The continental shelf in this region is relatively narrow, declining steeply some 4000 meters to the Molokai Fracture Zone which is a major abyssal plain (Couper, 1983:21). The ocean floor in this area consists of calcareous (calcium carbonate) sediment near the coast and becomes pelagic clay farther out to sea (Couper, 1983:43). Currents in the area are relatively mild at .5 knots which follows the coast southerly in the summer months, but can reverse in the winter to about the same speed (Couper, 1983:50). Surface currents decrease exponentially with depth (Smith, 1996: 54). Storms dominate weather patterns in the winter months (Bailey, 1966:48).

Marine Transport

Marine action transports materials through two primary mechanisms. Advection is movement with the current. Given a velocity, consisting of speed and direction, and a

concentration, the transport mechanism in mass/time/area can be defined. Diffusion, in a marine transport context, is the transfer of materials down a concentration gradient caused by turbulent mixing. To oceanographers, this refers to an active mixing process, and not passive movement at a molecular level. Defining the diffusion rate per square unit of area of the water is the product of the concentration gradient and the eddy diffusion coefficient. The concentration gradient is defined as the change in concentration over a distance. The eddy diffusion coefficient, a measure of intensity of the turbulent mixing, is the product of the current speed and the distance from the barrier that is causing the eddies. This barrier can be the ocean floor, the shore, or other particles of water with a different velocity. Pycnoclines, the boundary between water parcels of different densities, inhibit turbulent mixing processes and suppress the formation of eddies. Pycnoclines are often caused by differences in temperature, but can be caused by other factors such as salinity (Smith, 1996:3). Turbulent diffusive processes are considered very important with regards to the transport of pollutants (Matsoukis, 1973:175).

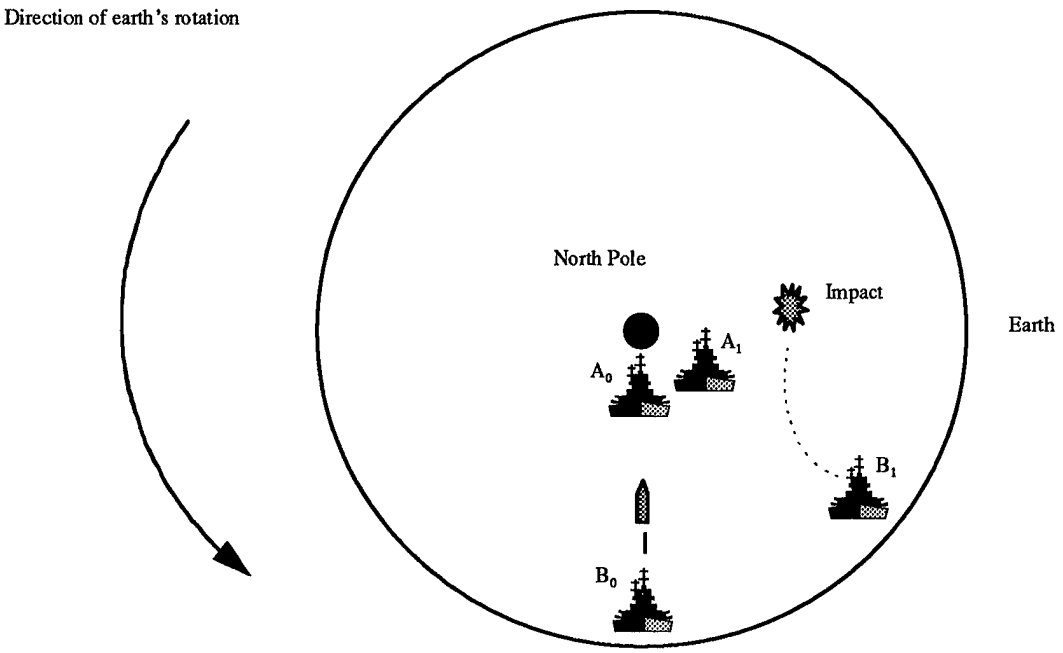
The vector sum of advection and diffusion describe the motion of a parcel of water. Numerous outside forces, such as coriolis, friction and pressure gradients, can also exert an accelerative effect on the motion of the parcel. Coriolis forces and friction play an important role with regards to a phenomenon called upwelling. Upwelling is movement of deep sea water over the continental shelf into shallow water (Smith, 1996:44). It is a significant ecological process because it provides nutrients from the benthic zone (ocean floor). However, this same process will move PCBs from the wreck to the shallow water ecosystem.

Pressure gradients can be broken down into a barotrophic pressure gradient and a baroclinic pressure gradient. The barotrophic gradient is caused by the slope of the water's surface. A point underneath a taller column of water is under more pressure than a point under a lesser column of water. Baroclinic pressure is the result of changing densities of water. A parcel under a more dense column of water will be under more pressure than one under a less dense column of water. In both cases the parcel of water under high pressure will be accelerated toward a region of lower pressure (Smith, 1996:4). Over time, these dynamic forces provide mixing.

Tides play a very important role in vertical mixing processes but don't result in significant net transport of materials. Net lateral transport is minimal because the tides cycle every 12.4 hours. This merely shifts materials back and forth, but does result in materials being well mixed. Asymmetry in tidal processes would result in net transport, but such asymmetry is dependent upon special bottom topography and coastline geometry (Blumberg and others, 1993:38)

Coriolis force is caused by the speed of the earth being slower as latitude becomes farther removed from the equator. If the earth is viewed from the poles, it can be seen that objects closer to the pole have a smaller circumference to travel in 24 hours than an object on the equator. An object transgressing latitude can thus seem to undergo an accelerative effect because of the differing speeds (An Online Guide to Meteorology, 1996). For example, two opposing warships sight one another in the northern hemisphere. There is no wind. "Ship A" is directly true north of "Ship B," which engages by firing a round directly at the target. The shell's velocity has two components: one true north from the gun, and one to the east from

the earth's rotation. The target is moving east also, but not as quickly as the shell from a faster moving latitude. From the perspective of "Ship B," the path of the shell will seem to have curved to the right. Coriolis force affects the movement of water and air and influences patterns of weather and current (An Online Guide to Meteorology, 1996). The situation is diagrammed in Figure 5.



Coriolis Force
(Ship B moves at a higher rate of speed than Ship A because of the earth's rotation and the ship's latitude as noted at times 0 and 1.)

Figure 5

Frictional forces acting upon a water parcel come from three different sources: wind shear, bottom friction, and internal shearing stresses (Smith, 1996:4). Wind blowing on the surface of the water will change the velocity of the water. Bottom friction is a velocity change resulting from the water's contact with the ocean floor. Internal shearing stresses result from

the water moving at a different velocity than surrounding water. Moving at a higher speed causes eddy currents between the faster parcel of water and slower surrounding water. Moving in a different direction than surrounding current will also cause eddies that tend to change the direction of the conflicting parcel of water. Density stratification suppresses the formation of eddy currents (Smith, 1996:5).

Upwelling

Upwelling results when surface water is moved out to sea by off shore winds or under special subsurface conditions. On occasions of violent storms, winds blowing out to sea produces a wind shear on the surface water. This moves the surface water seaward, creating a vacuum behind that can only be filled by bottom water (there are no other places for appreciable water to come from). This upheaval carries many deep ocean floor sediments and nutrients to the shallow water coastal area (Smith, 1996:44). Such wind action is the dominant upwelling factor. The broad and persistent north-east trade winds (out of the noth-east, traveling in a south westerly direction) of the northern hemisphere make the western coast of the United States of America one of the most major upwelling zones in the world (Barnes and Hughs, 1988:11,13, 38-39). These winds are typically from 6-9 miles per hour (Navarra, 1979:170).

Water can also be deflected toward the surface as a result of coriolis and friction forces. A southerly running current along the continental shelf in the northern hemisphere is held in balance between coriolis forces trying to turn it to the west, and friction against the shelf which slows down the parcel, deflecting the current to the east. In areas where bottom

friction is high, the friction force can overcome the coriolis force and cause the current to turn east toward the shelf. This slower speed acts to reduce the effects of the coriolis force and push the parcel of water toward the shelf even more. This phenomenon doesn't transport the mass in a short time period that upwelling from storms does, but is consistant over time to be the dominant upwelling mass transport process (Smith, 1996:47).

A northerly current with an eastern boundary is already being turned toward the coast by two forces which are acting in the same direction, but not reinforcing one another. As the friction slows the current to turn it toward the east, the coriolis force turning the current to the east becomes less. Upwelling by subsurface currents typically does not result in this case (Smith, 1996:47).

The vertical velocity of upwelling cannot be measured with a current meter. Instead, equations are used with field data to determine a rate. These vary widely in the literature. In a study of cadmium transport off the California coast, the upward transport of subsurface water occurred at a rate of 0.1 to 1.0 meters per day (Martin and others, 1976:181). In Atmosphere-Ocean Dynamics, Gill presents a typical value of coastal upwelling at 5 meters per day, but does not give a location (Gill, 1982:404). Studies in Peru off of Paitta give vertical velocities of 12 meters per month for fall, increasing to 58 meters per month in the winter. The San Juan area had a faster vertical water speed of 54 meters per month for fall increasing to 103 meters per month in winter (Zuta and others, 1978:243-245). Vertical water movement around Antarctica is on the order of 20 million meter^3 per second with the resulting current felt all the way to the equator (Barnes and Hughes, 1988:14-15). These

movements are large in comparison to the vertical migration of water through the thermocline at 0.5 to 1.6 centimeters per day (Steele, 1974:26).

PCBs can be transported to the shallow water system in free water as discussed above or while partitioned in mobilized sediment. Moving the sediments takes more energy than a parcel of water. The threshold of grain motion must first be overcome. This is the speed of water needed to put in motion a sediment particle of a given size and density (Smith and others, 1972:69). In general, the amount of suspended material increases with current speed (Smith and others, 1972:174). In the Washington area which shares many California coast currents, sediment transport only occurs during a few storms each winter (Smith and others, 1972:176). Because of isolating effects from the overlying water column caused by temperature gradients, suspended particles close to the ocean floor have estimated residence times of 100 days in this bottom layer (Richter and others, 1994:8).

Biogeographics

The exercise area is classified as warm temperate with regard to marine biogeographical classification because of its water temperature range of 10-20 degrees Celsius (Couper, 1983:68). The ocean itself consists of a diverse number of environments divided by physical properties such as light penetration, topography (location relative to the continental shelf), depth of the water, and depth that the organisms live (Lalli and Parsons, 1994:9). PCBs from the wrecks will first enter the marine ecosystem at the bathyal benthic. Benthic refers to the bottom regardless of the depth and bathyal refers to a bottom depth of 2000-3000 meters. In addition, contact will be made with organisms of the pelagic environment

which refers to the open sea. Such species are classified by the depth at which they live. The bathypelagic refers to the region between 1000-4000 meters. The mesopelagic includes depths from 200-1000 meters and the epipelagic is shallower than 200 meters. The continental shelf edge is generally 200 meters in depth (Lalli and Parsons, 1994:8).

The bathypelagic zone has a very low concentration of animal life (Couper, 1983:75). This deep sea region is a very harsh environment under extreme pressure (400-600 atmospheres) with an average temperature of 1 to 3 degrees Celsius (Rowe, 1983:261). However, sufficient oxygen is available in deep sea habitats to carry out aerobic metabolism (Rowe, 1983:306). In general, ocean circulation insures that sea water has a good supply of oxygen regardless of depth (Barnes and Hughes, 1988:15).

Residents of upper zones do not migrate to these depths (Couper, 1983:75). Shallow living fish do not have adapted enzymes to colonize the deep water nor is the food supply sufficient to encourage migration. Since food supply and the calories in this food decrease exponentially with depth, organisms have reduced metabolic rates and enzymatic activity in muscle tissue. Deep sea fish do not have energy available for running down prey (Rowe, 1983:262). Modest currents in the deep sea also minimize the demands for a powerful muscular/skeletal system capable of propelling such creatures at speed (Rowe, 1983:294-295). Since the species that do live there are carnivorous and not capable of prolonged swimming, they use artificial lights to attract and lure prey (Couper, 1983:75).

Since bathypelagic organisms can't cope with mesopelagic currents and mesopelagic organisms lack the enzymes to survive the bathypelagic, biological mixing does not occur.

Although linked by detritus, the deep sea and shallow water ecosystems are essentially independent.

Marine Ecosystem Models

With the exception of the North Sea, where interest is stimulated by the large fishing industry, marine ecosystems have not been studied sufficiently to effect realistic computer models. As a result, all such models abstract species and relations between them into some type of functional group. Such groups are defined by fixed parameters with highly uncertain values (Baretta and others, 1995:234). Food webs are difficult to quantify because few marine systems have been sufficiently studied to determine energy budgets to be used in food web model pathways (Lalli and Parsons, 1994:122). Parameters for the food web are thought accurate if they are within an order of magnitude of observed values (Klepper, 1995:39). No data exists that can be used to validate the relationships of the benthic environment so most modelers have avoided any explicit representation of benthic members (Baretta and others, 1995:239,241). The relationship between the nutrient cycling of the pelagic and benthic environments is also not well understood (Malmgren-Hansen and others, 1991:3). While nutrient levels in major standing stocks are known, the magnitude of nutrient transport within the marine ecosystem is still a mystery. This lack of knowledge is currently a main focus of marine ecology (Barnes and Hughes, 1988:295). Finally, modeling the marine ecosystem requires input from a diverse number of fields such as biology, ecology, chemistry, geology, and physics. Most models to date have been designed by small groups of individuals

that lacked the breadth and depth of necessary proficiencies (Malmgren-Hansen and others, 1991:3).

The Food Chain

Food chains depict the linear transfer of energy from one trophic level to another. Trophic levels consist of organisms that obtain their energy in similar ways. The very first trophic level in any ecosystem are the primary producers which change inorganic nutrients into living biomass. They are fed upon by the primary consumers. Each increasing level feeds upon the one below and are designated secondary consumers, tertiary consumers, etc. Energy flow up the levels is unidirectional, with organisms receiving energy from organisms at the next lower level and not the higher levels. Much of the absorbed energy is dissipated in the form of heat in conjunction with respiration and motion. The ratio between the inflowing energy at one level and the inflowing energy in the trophic level below it is referred to as the energy transfer efficiency. Energy transfer efficiency between trophic levels of the marine environment varies from 20% for the herbivores feeding on the phytoplankton and to 15-10% for carnivores at higher trophic levels. Energy transfer efficiency decreases as the trophic levels ascend (Barnes and Hughes, 1988: 68; Lalli and Parsons, 1994:115-117; Steele, 1974:22). Marine trophic ecological efficiencies are generally higher than the 10% found in terrestrial ecology. The more plentiful food is, the less efficient the transfer from one trophic level to the next. The ecotrophic efficiency between herbivores and phytoplankton can range from 5% to 90%. (Barnes and Hughes, 1988:68).

Assimilation efficiency of food also varies from level to level with herbivores at 0.3 and carnivores at 0.8. Herbivorous filter feeders such as mussels and clams have efficiencies ranging from 0.3-0.6. Food taken in, but not absorbed, is excreted (Connolly, 1991:764). The higher uptake values for carnivores result because the structure of their food closely resembles their own. Herbivores must break down plant cell structure, including cellulose, and convert it to animal tissue. This extra effort reduces efficiency. The lowest efficiency of carnivores are the scavengers with less than 0.4 because most of their diet consists of skeletal structures which are not digestible (Lalli and Parsons, 1994:132).

The loss of energy transfer from trophic level to trophic level puts a finite limit on the number of trophic levels in the ecosystem. In coastal areas out to the continental shelf region, it is generally accepted that there are four trophic levels. Upwelling regions can result in only three levels in cases that involve baleen whales because the dominant phytoplankton involved (chain-forming diatoms) is relatively large. The relative size of the dominant phytoplankton organisms in a food chain influences its length. The open ocean environment can have up to six trophic levels because the dominant phytoplankton (flagellates) are very tiny (Lalli and Parsons, 1994:118-119). It is the smaller organisms at the lower trophic levels which are ecologically important. Large predatory animals such as sharks and dolphins are only of social and political importance. While these top level organisms have the capability to shift the structure of the ecosystem depending upon feeding habits, the energy and nutrient flows in the highest trophic level are relatively insignificant compared to the rest of the system. Bacteria pass on twice the organic carbon to the next higher trophic level as does herbivorous

zooplankton (Malmgren-Hansen and others, 1991:4,5). Marine trophic levels can be expanded to encompass some terrestrial animals and special species.

The coastal area, consisting of four trophic levels, begins with the phytoplankton. Phytoplankton's growth is limited by light level in the winter months, or by available nutrients in the summer months. Large zooplankton in the pelagic, and clams and mussels in the benthic feed on the phytoplankton. Both are essentially herbivores (Lalli and Parsons, 1994:119). Asiatic clams are efficient collectors of PCBs because of their high lipid content (Colombo and others, 1995:923). Similar species of shellfish may accumulate PCBs in a like manner as shown by experiments involving the blue mussel and ribbed mussel (Nelson, 1995:516). Carnivores, such as herring in the pelagic and cod in the benthic, feed on their respective herbivores (Lalli and Parsons, 1994:119). This distinction is potentially important because of PCB's high sediment/water partition coefficient. Both carnivores will be fed upon by carnivores that eat other carnivores. These tertiary consumers consist of larger predators such as dolphins and sharks (Lalli and Parsons, 1994:119). Dolphins off the coast of southern California have the highest concentrations of PCBs in the world (Kamrin, 1994:69). Common dolphins in this area may have concentrations ranging from 80 to 300 ppm (Gaskin, 1982:405).

Sharks, despite sharing a common trophic level and function in the ecosystem with dolphins, have a different potential for PCB uptake. Sharks have 5 to 7 pairs of gill slits which will give them a PCB bioaccumulation pathway that dolphins do not have (Castro, 1983:12). Sharks consist of 350 different species of which 108 live in North American waters (Budker, 1971:9; Castro, 1983:3). Migrations of sharks are not understood, but it is assumed

that since they are predators, sufficient food will discourage them from leaving the area of interest (Castro, 1983:24). Sharks seem to have no preference in prey with both pelagic and benthic species found in the stomachs of sample animals. Food intake is thought to be around 1.2% of body weight per day (Budker, 1971:94,99). Unfortunately, PCB accumulation data for sharks was not readily available for comparison to dolphins and other mammal predators.

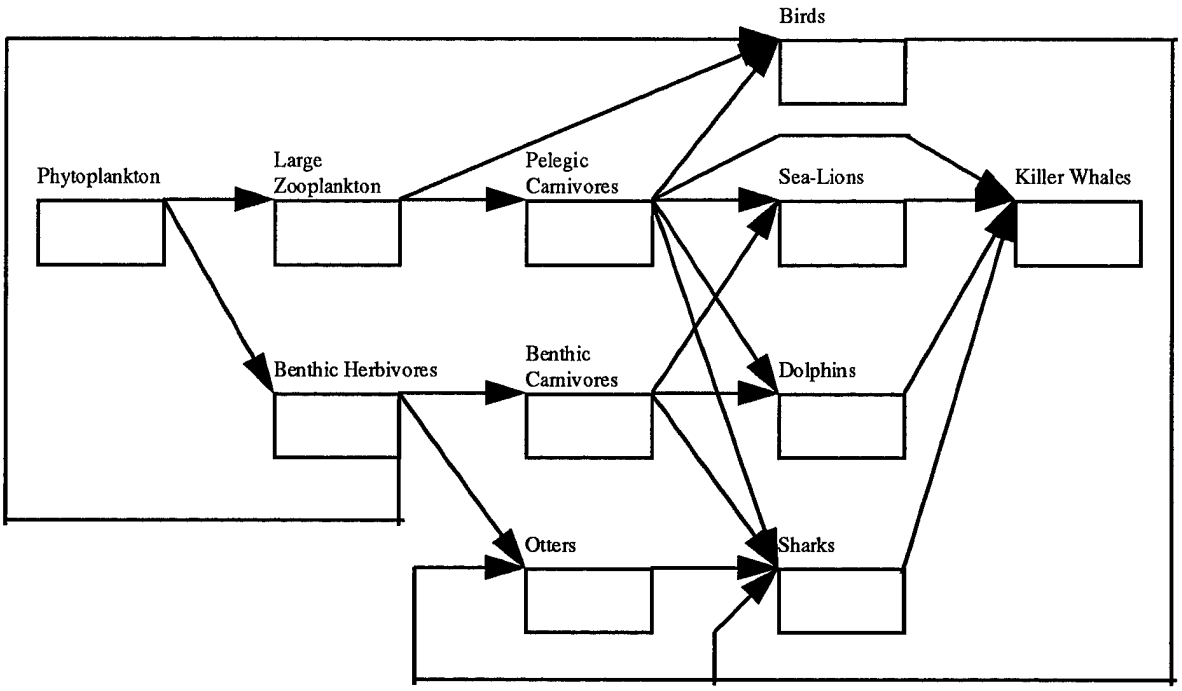
Terrestrial mammals and birds that venture into the marine environment show substantial evidence of PCB uptake although the exact pathways are not known. Otters, which feed on shell fish, have had PCB concentrations ranging from nondetectable to 300 ppm. Five of every 23 animals sampled were in excess of 50 ppm (Kamrin, 1994:66). PCBs are considered responsible for the otter's decline in Oregon (Mason and others, 1986:97). Otters have a home range and do not migrate (Mason and others, 1994:24). Their diet consists of bottom living species and invertebrates, but they have been known to eat birds as well. Food intake can be one fourth their body weight per day and they average in mass around 32 Kg (Mason and others, 1994:22,193-194). They have few natural enemies except for white sharks (Mason and others, 1994:198).

Sea-lions feeding on pelagic fish had PCB concentrations from 21-34 ppm (Kamrin, 1994:68). PCBs, along with heavy metals, are considered a factor in spontaneous abortions of California Sea-Lions. Sea-lions are opportunistic feeders capable of eating a wide variety of organisms and average in mass around 255 Kg (Bonner, 1994:59,69,208). PCBs have also negatively impacted the reproductive capacity of harbor seals in Puget Sound (Hong and others, 1996:837).

Observable effects from PCBs are documented in sea bird experiments as well (Bosveld and others, 1994:103-110). There are 300 species of seabirds and it is suspected that more species will be discovered (Löfgren, 1984:21). Diet varies by species with the gauntlet running zooplankton, krill, crustaceans, and fish. Shellfish are cracked open by being dropped from altitude onto rocks (Löfgren, 1984:131,148). Large flocks of birds have been known to converge on upwelling areas to feed as well (Nelson, 1979:171). Birds travel in continual wandering, eventually returning home (nomadism) or by alternating specific homes for feeding and mating purposes (migration) (Nelson, 1979:170). Terrestrial predators result in high rates of infant mortality, but birds reaching maturity can expect to live into their 30's and 40's (Nelson, 1984:165). Sharks occasionally claim deep diving birds, but more likely death is brought on by disease, harsh weather, or old age (Löfgren, 1984:156). The average life span is 8.5 years (Nelson, 1984:165).

At the very top of the marine food chain is the killer whale, or orca, which has no natural enemies except for man and other killer whales (Leatherwood and Matkin, 1986:56). Killer whales have been frequently sighted off the California coast and eat fish, sharks, and mammals to include sea-lions, dolphins, and large baleen whales (Leatherwood and Matkin, 1986:47-48; Hall, 1986:77). They hunt in pods of 5 to 20 animals and 20 pods are known to operate off the Washington coast. The average killer whale weighs 6 tons and is thought to have an average life span of 48 years, but may live closer to 100 years (Leatherwood and Matkin, 1986:36,46,49,57).

A diagram of the coastal food chain is presented as Figure 6.

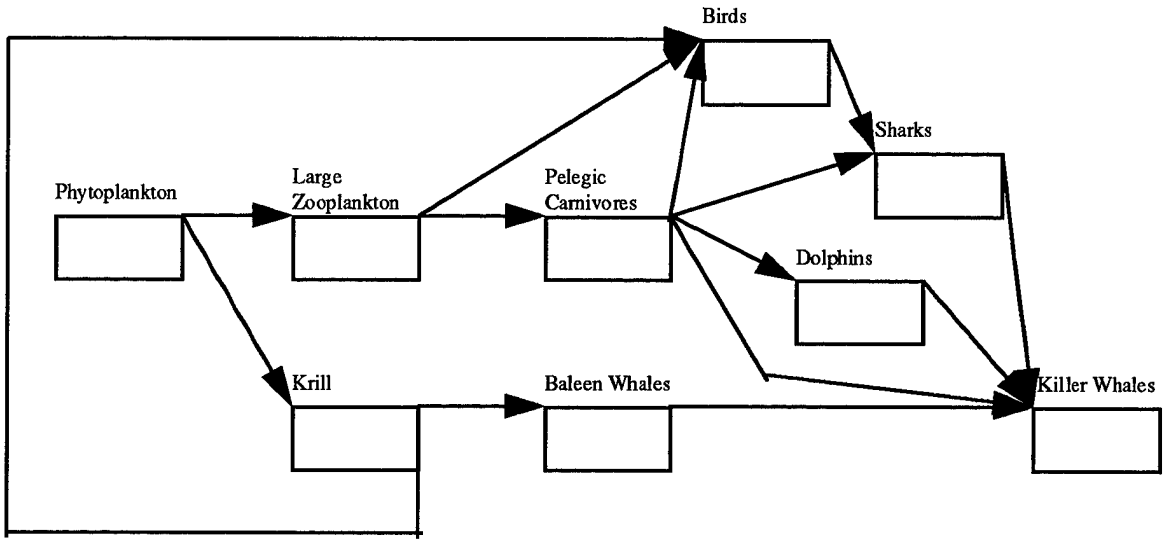


Coastal Food Chain

Figure 6

Upwelling at the shelf eliminates nutrient constraints on growth causing large blooms of phytoplankton. The relative number of species in upwelling zones is small, but the size of the species is large and they generate huge productivity compared to their own biomass (Barnes and Hughes, 1988:74). The start of this chain can continue as the pelagic shallow water chain or take a shorter three trophic level route. Krill feeding on the phytoplankton are the primary food source for baleen whales. These baleen whales cap this chain at three trophic levels (Lalli and Parsons, 1994:119). The baleen whales spend the Antarctic summer (November to April) feeding on rich krill populations and migrate to warmer equatorial waters to mate. During this mating period the adults do not feed. (Couper, 1983:78). It is possible that some feeding could occur though in the exercise region by sexually immature animals or

well timed blooms occurring with migrates. Such animals are of political importance and the blue whale's life span of 50 years provides much time for accumulation of PCBs (Couper, 1983:78). Most baleen whales typically live for 30 to 40 years (Gaskin, 1982:307). A schematic is presented as Figure 7.



Upwelling Food Chain

Figure 7

Production in upwelling areas is much higher than in the rest of the ocean because nutrient constraints are not as binding. This production averages 625 mg C per m^2 per day, but can be even higher (Barnes and Hughes, 1988:39; Dawes, 1981:552). This phytoplankton is eaten nearly as quickly as it is produced, with almost all going to herbivores (Steele, 1974:5). In concurrence, Dawes assumes that the standing mass of phytoplankton is the net production, with the difference of net and gross production lost to the zooplankton (Dawes, 1981:551). Although data in the literature is sparse according to Barnes and Hughes, secondary production reflects the distribution of primary production. Zooplankton has seldom been measured, and when it has it usually represents only one species. Zooplankton

production is thought to be around 75 mg C per m^2 per day in upwelling areas (Barnes and Hughes, 1988:65). The herbivores are limited by food and not by pressure from carnivores (Steele, 1974:5; Barnes and Hughes, 1988:65).

The relevent bathyalbenthic food chain can be dipicted as a straight line arrangement of three trophic levels: PCB degrading bacteria, worms that eat these bacteria, and carnivorous fish feeding on these worms. These animals are currently of no economic or social value, but PCBs tied up in their bodies are not available for biodegradation or transport to coastal waters (Nybakken, 1982:132,152).

Modeling by trophic levels has many inherent problems. Some species are omnivores that feed on both plants and animals and thus don't fit in well to a particular trophic level. Some species change trophic levels as they grow or because of changing food supply availability. The relative numbers of species can have an impact on upper trophic levels even if the amount of biomass involved remains the same. Finally, certain species at a given trophic level do not eat all species in the level below it (Lalli and Parsons, 1994:120-121). The structure of the food web, the height of the trophic level, and the length of the trophic level chain make an important difference in the uptake of PCBs (Campbell and others,1995:4). Another problem concerns those organisms that are larger and longer lived. These animals have very different growth and respiration rates over their life cycle. The approximation of identical equal sized organisms made at lower trophic levels does not hold. This involves a scaling problem when data is taken on an individual to create a model parameter. The information must be scaled for all organisms in the population and then again across all species in the group or trophic level. This leaves very little chance of validation (Baretta and

others, 1995:236-237). An example would be older organisms which typically have a higher lipid content than younger organisms of the same species, which results in higher rates of PCB uptake (Vassilopoulou and others, 1993:287).

PCB Uptake

PCBs are taken up by two mechanisms: bioaccumulation and biomagnification. Bioaccumulation is based upon the partition coefficient of the material between the organism and water. Since this ratio is seldom known and varies between species, it is approximated with the octanol/water partition coefficient (Covello and Merkhofer, 1993:114). For a lipophilic compound, the higher the mass of lipids in the organism, the more contaminant it takes up. The concentration in an organism's body will vary with varying lipid levels. Lipids are an important energy source for fish which are utilized in the winter months when food is scarce or when migrating (Porte and others, 1993:275). The bioaccumulation rate of PCBs for filter feeding animals is a function of the intake of suspended particles when such contamination is continuously cycled through the animal (Colombo, 1995:926). In noncontaminated water, the gills will provide the major site of expulsion of organic compounds. Fecal elimination is not significant (Connolly, 1991:763). The biota sediment accumulation factor (BSAF), the partitioning coefficient between lipids and sediments, varies with sediment type (Boese and others, 1995:309). In general, experiments show that BSAF also declines with increasing PCB chlorination, but there were a few exceptions with pentachlorinated and hexachlorinated congeners (Boese and others, 1995:307).

For metabolic purposes, organisms ingest other organisms. The material then proceeds up the food chain in greater and greater concentrations, resulting in biomagnification. Predators at the top of the food chain can thus accumulate large amounts of PCB materials compared to concentrations in the ecosystem around them. Research and sampling has proven that organisms of higher trophic levels can accumulate PCB concentrations far above what they would have based on partitioning (Spacie, A. and others, 1995:514; Bright and others, 1996:2507). There is an absence of a relationship between PCB concentration and lipid content for higher organisms (Stow, 1995:527). Highly chlorinated PCBs are not as readily absorbed by the intestines as lightly chlorinated PCBs (Colombo and others, 1995:926).

PCB sources for biota include the sediments, the water column, and other contaminated biota (Connolly, 1991:765). Species will thus accumulate the material through bioaccumulation and by consuming other contaminated organisms for metabolic purposes. The relative significance of each pathway is still under debate. However, food uptake of PCBs by lake trout and Lake Michigan salmonids dominates uptake by the gills (Vassilopoulou and others, 1993:287; Jackson and Schindler, 1996:1864). Ignoring gill exchange in PCB uptake estimation still results in realistic results (Jackson and Schindler, 1996:1861). PCBs will also be passed on to offspring by adults. Research has shown that concentrations of PCBs in the gonads of both benthic and pelagic fish is 10 times higher than the concentration in other organs such as muscle and liver. It was concluded that accumulated PCBs are passed on to offspring (Porte and Albaigés, 1993:275). Cycling PCB

concentrations varying from a high in March to a low in June for red mullets off the Greek coast is attributed to mating cycles (Vassilopoulou and others, 1993:286).

The small mass of individual phytoplankton and corresponding relatively large surface area allow the calculation of PCB uptake directly from K_{OW} since assimilation is rapid. For zooplankton, uptake can be calculated from K_{OW} using the amount of chemical that is freely dissolved in the water (that didn't partition into the sediments) (Spacie, A. and others, 1995:508-509). However, the assumption of equilibrium between the phytoplankton and water can lead to biased results since accumulation probably also takes place in non-lipid components of the phytoplankton. Nevertheless, instantaneous equilibrium may still apply to small organisms (Skoglund and others, 1996:2114,2117,2120). Benthic organisms' whole body PCB levels are similar to the concentration in the sediment. Exceptions are filter feeders such as bivalves that will uptake via the suspended solids route. Benthic organism's constant exposure to PCBs in the sediments is considered an important pathway in predator's food chain uptake (Spacie, A. and others, 1995:508-509).

Metabolization of PCBs

PCBs can be metabolized by some plants and animals. In plants, this depends on the plant and the particular congener involved. There is a correlation between the rate of metabolism and the PCB's physical properties. Research at present has used only terrestrial species (Bokern, 1995: 2019). Numerous organisms can metabolize PCBs into other compounds which are readily excreted (Bright and others, 1996:2504). Given the large number of marine species, it is not inconceivable that some of them are capable of

metabolizing PCBs. Research on marine animals does demonstrate some metabolism depending upon feeding patterns and metabolic capabilities of the organisms involved. However, this metabolism is generally small enough that PCBs are still biomagnified in food chains (Porte and Albaigés, 1993:277). Such metabolism by plants and animals is not well quantified and involves a diversity of species. The EPA considers PCBs to be highly resistant to metabolic degradation (EPA, 1991:12-1).

Time Scale

A long time scale is appropriate in modeling persistent pollutants such as PCBs. This is not unique to marine modeling efforts. Typically it is long run values which are of interest when modeling ecological processes and as such there is little value in trying to model on short time scales (Klepper, 1995:41). Despite the ocean's dynamic nature, it isn't necessary for a model to be dynamic. Steady state values of large time step models vary little from the output of the more complicated and detailed models (Klepper, 1995:39). Therefore study of the fate and transport of PCBs does not require detailed analysis of the complicated relationships resulting from nutrient dynamics.

U.S. Navy's Model

In the U.S. Navy's original modeling effort, the sunk vessel was modeled as a 20 meter high cylinder with radii of 40 meters and 25 meters for large and small ships respectively (Richter and others, 1994:9). It was assumed that there was 30 pounds of PCBs

on board a typical ship, and no more than 100 pounds on a large one. Depending upon their media, location, or function, some PCB materials are assumed to remain with the ship. Bulkheads and watertight doors for all practical purposes permanently isolate some materials from the marine ecosystem. In addition, PCBs in plastic type insulation used in electrical wiring were found to be nonmobile in laboratory experiments and are assumed to be permanently bound (Richter and others, 1994:2). Thought to be very mobile are PCBs in felt gaskets. Of the total PCBs aboard the Ship, 65% was assumed to be capable of leaving the ship (Richter and others, 1994:2).

The formulation to model this release is based upon laboratory data on gaskets resulting in 0.194 g day^{-1} of PCBs being released from a large ship and 0.058 g day^{-1} from a typical ship. The larger ship has more surface area exposed to the ocean and could be expected to introduce PCBs at a higher rate. The rates may be high, as the much colder temperatures in the deep could make actual release much slower (Richter and others, 1994:9). A steady moderate current of 5 cm sec^{-1} that dispersed the chemicals was assumed. After release, the PCBs were assumed to become mixed in the upper level of the sediments from bioturbation (disturbance of sediment by organisms) and sediment renewal (disturbance of the sediments by physical processes). The highest sediment concentration occurred at the hull of a large ship at 44 ppb and the highest water concentration was 0.0028 parts per trillion (pptr) (Richter and others, 1994:2). This outcome is considered consistent with historical data. Background levels of PCBs in the open ocean are typically in the pptr range. Sediments, which tend to accumulate PCBs, have levels up to seven orders of magnitude higher (Richter and others, 1994:3). The results of the model are that any contribution of

PCB materials to abyssal water (between 2000-6000 meters) from the sinking of a Navy ship will be much less than background PCB levels. Sediment concentrations are above a nominal background level of 10 ppb for some time. Based upon shallow water toxicity data, this would not be toxic to benthic organisms (Richter and others, 1994:3).

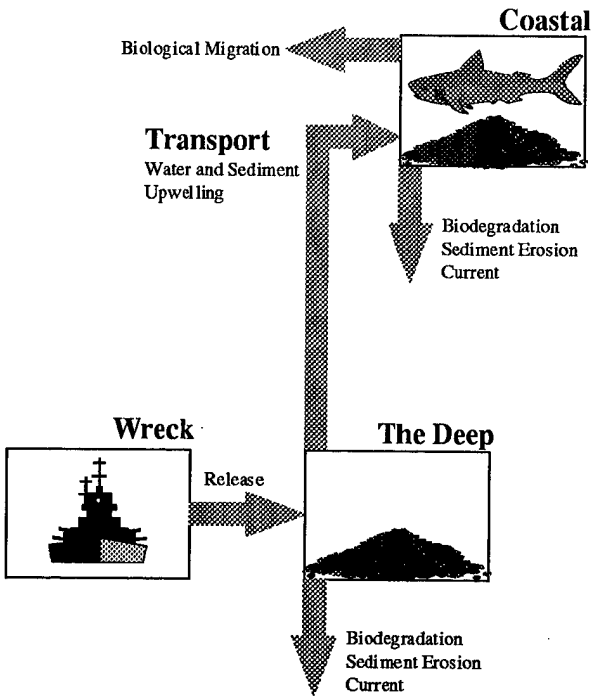
The model assumed a "benthic boundary layer" which buffered the area around the wreck from the rest of the ocean. At depths greater than 3000 meters, a turbulent layer 10-100 meters thick exists on the bottom that is isolated from other water by a temperature induced pycnocline (Richter and others, 1994:8). Sediments were assumed to have an infinite absorptive capability at the PCB levels of relevance (Richter and others, 1994:9). As previously mentioned, sediment residence times here are assumed to be hundreds of days (Richter and others, 1994:8). These two assumptions make possible the belief that the chance of PCBs leaving deep waters is remote (Richter and others, 1994:13).

While the average depth of sinking may be as much as 3900 meters (as 12 records indicate), this is far deeper than the current requirement (Richter and others, 1994:9). At the minimum regulation sinking depth of 6000 feet, the wreck is above the deep abyssal plains and the assumption of a "benthic boundary layer" does not hold. Secondly, the model was run on a time scale of 100 model hours (Richter and others, 1994:9). This is much too short to evaluate transport given PCB's persistency of many years, especially when the current speed used in this model is capable of eroding sediment (Richter and others, 1994:8). Finally, the only transport mechanism examined was the dispersal current of 5 cm sec^{-1} (Richter and others, 1994:9).

III. Methodology

System Description

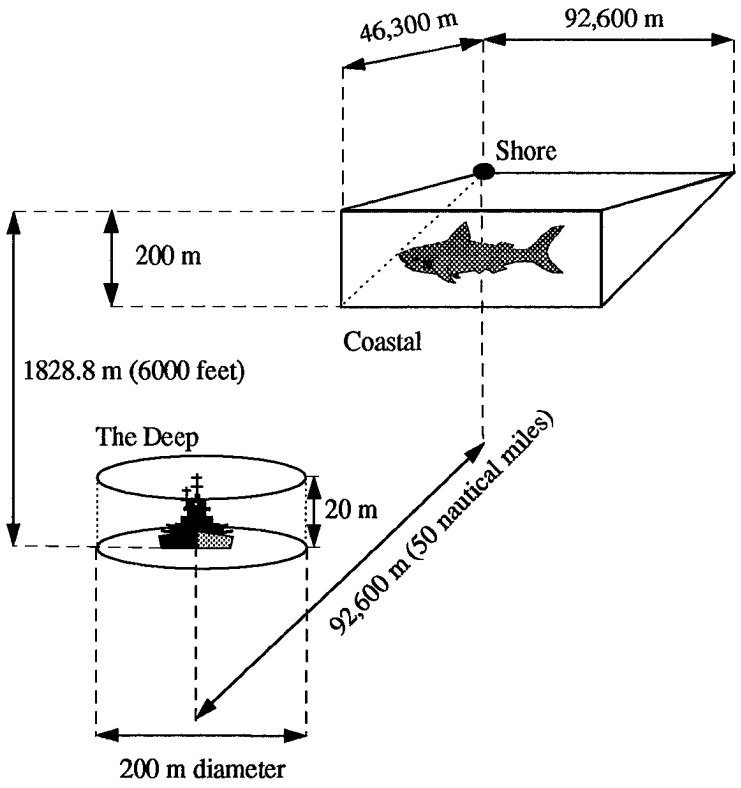
Limited information from actual SINKEXs is available. Therefore the model uses a hypothetical sinking meeting legislative requirements (6000 feet of water, 50 nautical miles from land) instead of an average of several wrecks. A continuous time modeling language, STELLA II, from High Performance Systems Inc. was used to conduct the research. The language utilizes the Runge-Kutta 4 algorithm for its calculations which is appropriate for oscillating processes (High Performance Systems, 1994:98). The model consists of three different modules: the Wreck, the Deep, and the Coastal. The Wreck represents the PCBs that are available to be released into the marine ecosystem. The Deep represents the bathyl environment around the wreck. Marine transport processes move PCB material from the Deep to the Coastal and remove material from the system by dispersing it out to sea. Biodegradation in the Deep Module also removes material from the system. Coastal represents the main area of interest, consisting of the area from the shelf edge to the shore. The Coastal is home to countless marine organisms. Various processes of biological transport, marine physical transport, and biodegradation can remove PCBs from the Coastal module. The system is diagrammed in Figure 8.



The System

Figure 8

A PCB source 92,600 meters (50 nautical miles) from land in 1828.8 meters (6000 feet) of water was used to represent the wreck. Dimensions of the system are given in Figure 9. The wreck contained 8845 grams (65% of 30 pounds which is the mass of PCBs capable of leaving the ship) of PCB material and released it into the deep water at 21.17 grams per year. This is based on the U.S. Navy's experiments and assumes a typical ship with the expected load of PCBs. Release is assumed to be constant and continuous (Richter and others, 1994:2).



System Dimensions

Figure 9

The available PCBs are divided into two separate stocks designated as heavily chlorinated PCBs (HPCBs) and lightly chlorinated PCBs (LPCBs). The division was made because of the biodegradation behavior of PCBs and the reduced oral uptake rate for heavily chlorinated PCBs (Abramowicz and Olson, 1995:38; Colombo and others, 1995:926). In the model, heavily chlorinated PCBs are those with five or more chlorine molecules attached that begin degradation anaerobically. The primary PCB material of concern is Aroclor 1260 (with 60% of the weight coming from chlorine) which is dominant in the mobile material found in felt gaskets (Richter and others, 1994:6).

In dividing the mobile PCB weight between the HPCB stock and the LPCB stock, two hypothetical molecules were assumed. For weight calculation purposes, the LPCB consists of 12 carbons and 2.5 chlorine atoms. The HPCB consists of 12 carbons and 7.5 chlorine atoms. This gives molecular weights of 232.6 and 409.9 grams per mole for LPCBs and HPCBs respectively. Given that the total mass of mobile PCBs on board is 8845 grams and that 60% of this weight is from the chlorine atoms in the molecule, it is possible to solve the following simultaneous equations:

$$232.6(grams/mole) \bullet L + 409.9(grams/mole) \bullet H = 8845(grams)$$

$$88.6(grams - of - Cl/mole) \bullet L + 265.9(grams - of - Cl/mole) \bullet H = 5307(grams - of - Cl)$$

L and H denote moles of LPCB and HPCB respectively. Solving these equations yields 6.9 and 17.7 moles of LPCB and HPCB which corresponds to a load mass of 1609 and 7236 grams of LPCB and HPCB.

The release rate of 21.17 grams per year is scaled so that both the LPCB and HPCB stocks in the Wreck will void simultaneously. The release rate for the LPCB stock is:

$$\frac{1609}{8845} \bullet 21.17 = 3.85(grams/year)$$

The HPCB release rate is calculated in a similar manner and results in:

$$\frac{7236}{8845} \bullet 21.17 = 17.32(grams/year)$$

The releases are assumed to be constant and no releasable PCBs are expected to be aboard a typical vessel after an elapsed time of just under 418 years. Release is to the corresponding LPCB Deep Water and HPCB Deep Water compartments.

Deep Rate Equations

The Deep holds two compartments for PCB residence: water and sediment. Each compartment is subdivided for LPCBs and HPCBs. Because the biomass at these depths is so low, PCB residence in organisms in the Deep is neglected (Barnes and Hughes, 1988:202). These PCBs under go partitioning to the sediments based upon the equation (Lara and Ernst, 1989:83):

$$\frac{C_{DS}}{C_{DW}} = K_{SW} = 10^4 \qquad (1)$$

C_{DS} is the concentration in the deep sediments in grams of PCB per cubic meter and C_{DW} is the concentration in the deep water in grams of PCB per cubic meter. K_{SW} is the partition coefficient between sediment and water for PCBs and generally accepted to range from 10^3 to 10^4 (Richter and others, 1994:6). The initial model assumed that both LPCB and HPCB have the same sediment water partition coefficient.

Concentration is defined as a mass divided by a volume. The volumes of the Deep Module were taken from the PCB distribution pattern of the U.S. Navy's model output. These can be represented by a pair of stacked cylinders with the top cylinder representing the deep water and the bottom one representing the sediments. The radius of these cylinders is 100 meters, which is the limit of distribution. After 100 meters, PCB

concentrations were below background levels. The water cylinder height is 20 meters based upon the height of the wreck. The sediments were assumed to be 0.1 meters deep since this upper 10 centimeters is where PCBs accumulate (Richter and others, 1994:10). Enough mixing was assumed to make partitioning valid.

Biodegradation takes place in the sediment compartment. HPCBs are returned to the system as LPCBs. This represents the anaerobic degradation process through reductive dechlorination. The rate that this occurs is given by the equation:

$$Rate_{ANAEROBIC} = .03285 \bullet HPCB \qquad (2)$$

HPCB is the mass of HPCBs undergoing degradation in Kgs. The factor 0.03285 has units of grams per Kgs-year. This gives an anaerobic degradation rate in grams of HPCB per year based upon field data (Harkness and others, 1993:505). Since anaerobic degradation occurs slower than aerobic degradation, the value used is from the low end of the overall observed degradation rate. This same rate is used in the Coastal Sediment compartment of the model discussed below.

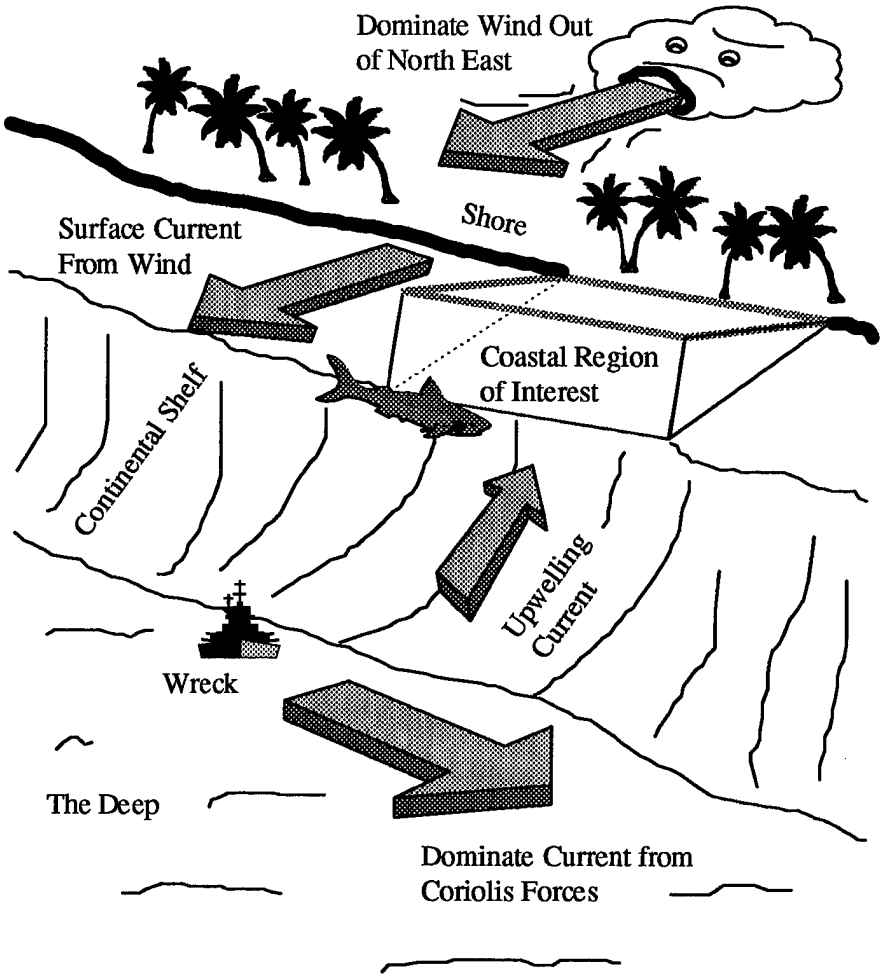
Aerobic degradation in the sediment removes LPCBs from the system by changing them into non PCB materials. This also occurs in the Coastal Sediment compartment discussed below, but sufficient oxygen exists in the deep sea for aerobic processes also (Rowe, 1983:306; Barnes and Hughes, 1988:15). This rate is given by:

$$Rate_{Aerobic} = .1752 \bullet LPCB \qquad (3)$$

LPCB is the mass of LPCBs aerobically degrading in Kgs. The factor 0.1752 has units of grams per Kgs-year giving an aerobic degradation rate in grams of LPCB per year. This

value is chosen from the higher end of observed field degradation data as aerobic processes occur faster than anaerobic ones (Harkness and others, 1993:505).

Physical processes act to move PCB material in the ocean. A diagram of such physical forces is presented as Figure 10.



Physical Transport Processes

Figure 10

Deep currents act to disperse the dissolved and suspended PCB materials in the depths. PCBs removed from the area of interest are assumed to be diluted by the vast

volume of the rest of the ocean to background levels. This is a function of the velocity of the current, the area of the water column, and the concentration of the PCB material in the Deep Water stock. This dispersion is given by:

$$Dispersion_{DEEP} = V_d \bullet A_{DWC} \bullet C_{DW} \qquad (4)$$

V_d is the velocity of the current and is 1.5 M meters per year. This is equivalent to a steady 5 cm per second current assumed in the original model (Richter and others, 1994:9). The area of the deep water column, A_{DWC}, is calculated by the dimensions of the Deep Water Compartment. The cylinder is 200 meters in diameter with a height of 20 meters. Looked at from the side, this is a rectangle with an area of 200 x 20 or 4000 meters^2. The concentration of the PCBs in deep water, C_{DW}, is given in grams per meter^3 resulting in dispersion units of grams per year. Concentrations of LPCBs and HPCBs in deep water are calculated separately in the model with both PCB types undergoing dispersion to the depths. The volume of the deep water compartment is given by $\pi \bullet r^2 \bullet h$ (Selby, 1970:16).

The deep currents cause erosion of the sediments which also removes PCBs from the system to be dispersed into the depths. This transport process is a function of the width of the water column, the concentration of PCB material in the sediment, the density of the sediment, and the velocity of the sediment. Sediment speed is a function of the water's speed and the grade over which the sediment is being moved. This rate is given by the expression:

$$Erosion_{DEEP} = W_{DWC} \bullet C_{DS} \bullet \nu_s \bullet V_{DS} \qquad (5)$$

W_{DWC} is the width of the deep water column which is 200 meters. C_{DS} is the concentration of the PCBs in the Deep Sediments in grams per meter^3 and is calculated separately for LPCBs and HPCBs. The volume of the Deep Sediment compartment is 3141.6 m^3. υ_s is the specific volume of the sediment, (1555 Kg per meter^3)$^{-1}$, based upon the density of calcareous sediment (Harte, 1988:245). V_{DS} is the velocity of the deep sediment in Kgs of sediment per meter per year given by (Smith and others, 1972:71):

$$V_{DS} = \frac{K \bullet \omega}{g \bullet \frac{\rho_s - \rho}{\rho_s}} \qquad (6)$$

g is the acceleration due to gravity at $9.753 \bullet 10^{15}$ meters per year^2 (based upon 9.8067 meters per second^2) (Lindeburg, 1992:1-2). ρ is the density of the fluid conducting the transport and is 1025 Kg per meter^3 for sea water (Lindeburg, 1992:ii). K describes the ability of the fluid to transport the sediment and ω is the power of the fluid. K is calculated from (Smith and others, 1972:71):

$$K = \frac{\varepsilon_b}{1 + \tan(\beta)} \qquad (7)$$

ε_b is the efficiency of the fluid in transporting the sediment which must be less than unity. The parameter .6 was utilized in the initial model. β is the slope of the surface on which the grains are being moved. In the Deep Water compartment of the model, a level grade was assumed for the area around the wreck. This gives K a value of 0.6 for the Deep Compartment.

The power of the fluid, ω, is calculated from (Smith and others, 1972:79):

$$\omega = 3 \bullet 10^{-3} \bullet \rho \bullet V_d^3 \qquad (8)$$

The entire erosion process is in grams of PCB per year and is calculated separately for LPCBs and HPCBs.

Storms

The above processes of dispersion and erosion are deep enough that storms do not overly affect them since wind turbulence generally only extends to a depth of 200 meters (Barnes and Hughes, 1988: 49). While surface currents increase during a storm, this current decreases exponentially with depth (Smith, 1996:54). However, storms do play a roll in the upwelling of both water and sediment from the Deep and all physical Coastal processes. Storms in the model are random. They occur 12% of the time in winter and 1% in all other seasons. This corresponds to the approximately two months of storms a year mainly occurring over the American west coast winters (Bailey, 1966:48).

Upwelling Equations

The upwelling of water, in the model, is a continuous process that increases during storms. The upward flow of subsurface water in the region has been calculated to range from 0.1 to 1.0 meters per day (Martin and others, 1976:181). The model uses the

midrange value of 0.5 meters per day during non storm periods and the highest observed value of 1 meter per day during storms. The mass transport equation is:

$$Upwelling_{WATER} = V_U \bullet A_{DWC} \bullet C_{DW} \qquad (9)$$

$Upwelling_{WATER}$ is in grams of PCB per year. The velocity of the water, V_U, is 182.5 meters per year and increases to 365 meters per year when a storm occurs.

Sediment can also be transported by upwelling processes, although it occurs slower than the movement of water. This transports mass by the equation:

$$Upwelling_{SEDIMENT} = W_{DWC} \bullet C_{DS} \bullet \nu_s \bullet V_{US} \qquad (10)$$

V_{US}, the velocity of the upwelling sediment, differs from V_{DS} because of storm activity and the upward slope to shallow water. K takes on a value of 0.5797 with β equal to 2.01° from a rise of 1628.8 meters over a 46,300 meter distance. ω changes with V_U above. $Upwelling_{SEDIMENT}$ is in grams of PCB per year with transport of LPCBs and HPCBs occurring separately.

Upwelling moves PCBs from the Deep to the Coastal system. Upwelling water enters the Coastal Water compartment and upwelling sediment enters the Coastal Sediment compartment. LPCBs and HPCBs are handled separately like in the Deep. The Coastal systems, in addition to having sediment and water stocks like the Deep, also have stocks representing marine organisms.

Coastal Equations

The coastal area is 200 meters deep as this depth typically corresponds to the depth of the continental shelf (Lalli and Parsons, 1994:8). The edge of the shelf is placed half way between the shore and the wreck, giving a coastal area that is 25 nautical miles (46,300 meters) out to sea. The width of 50 nautical miles (92,600 meters) was selected as this was twice the travel distance of the upwelling materials and reasoned to have a good chance of capturing the upwelling PCBs.

Biodegradation processes occur in the Coastal Sediments in the same manner as in the Deep Sediments. HPCBs in the Coastal Sediments are returned to the Coastal Sediments as LPCBs at the previously defined anaerobic degradation rate in Equation 2. LPCBs in the Coastal Sediments are removed from the system at the previously defined aerobic degradation rate in Equation 3.

Dispersion of PCBs in the Coastal Water stocks (one each for LPCBs and HPCBs) occurs in a similar manner to the Deep Water stocks, except that the PCBs are exposed to the higher surface currents and a larger water column. Materials dispersed are assumed lost to the system in the vastness of the ocean. The equation in grams of PCBs per year is:

$$Dispersion_{COASTAL} = V_C \bullet A_{CWC} \bullet C_{CW} \qquad (11)$$

V_C is the velocity of the coastal current and its value of 8 M meters per year corresponds to a surface current speed of 0.5 knots. It increases by an order of magnitude during a storm. The area of the coastal water column, A_{CWC}, is 18.52 M meters^2. The height of 200 meters was multiplied by the width of 92,600 meters. C_{CW} is the PCB concentration

of the Coastal Water in grams per meter^3 and is calculated separately for LPCBs and HPCBs. Volume of the Coastal Water is 428,738 M meters^3 which takes into account the slope of the coastal ocean floor.

Coastal erosion occurs in the same manner as the depths, but subject to coastal parameters as given by:

$$Erosion_{COASTAL} = W_{CWC} \bullet C_{CS} \bullet \upsilon_s \bullet V_{CS} \qquad (12)$$

$W_{CWC,}$ the width of the coastal water column, is 92,600 meters. C_{CS} is concentration of PCBs in grams per meter^3 in the Coastal Sediments and is calculated separately for LPCBs and HPCBs with a volume of 428.742 M meters^3. V_{CS}, the velocity of the Coastal Sediments, differs from other sediment velocities with the higher current speed which is subject to storms and the downward slope of the coastal area. K has a value of 0.603 since β is a negative 0.247°. $Erosion_{COASTAL}$ is in grams of LPCB or HPCB per year.

Partitioning occurs in two instances in the Coastal System. The first is between the sediments and water. This is similar for the Deep Module and given by:

$$\frac{C_{CS}}{C_{CW}} = K_{SW} = 10^4 \qquad (13)$$

Partitioning also occurs between the water and marine organisms. In order to calculate a ratio of concentrations, the volume of marine organisms is needed.

Marine Organism Equations

A systems dynamic approach is used to determine the volume of organisms at a point in time for use in calculating PCB concentration. The model utilizes a four level predator-prey infrastructure as outlined in Stella II, An Introduction to Systems Thinking (High Performance Systems, 1994:98-99). Each level has a birth rate based upon that level's productivity and the amount of standing biomass it currently has. New biomass entering a stock representing the given trophic level is the product of the standing biomass and this birth fraction.

Each level exerts a death rate on the level below it through predation. A level exerts a death rate on the level above it through insufficient prey density. The bottom trophic level is assumed to only parish as prey and the top trophic level only by lack of prey. This includes old age, as older predators aren't able to run down prey to maintain metabolism. The biomass leaving the stock representing a given trophic level can be defined as the product of standing biomass and a death fraction.

The first trophic level is the Primary Producers which are predominately phytoplankton. A standing stock of 10 mg per m^2 and a Productivity Fraction of 62.5 to give an initial production rate of 625 mg per m^2 is used to provide typical values for upwelling areas (Barnes and Hughes, 1988:39-40; Dawes, 1981:552; Harte, 1988:257). The amount of available sunlight is a major factor for phytoplankton productivity. This was expressed as a sinwave that varied over a period of one year. Amplitude of the sinwave ranged from 0.85 to 1.15. When multiplied by the Primary Producer's

Productivity Fraction it provides a range of typical productivity values measured throughout the year (Barnes and Hughes, 1988:39).

Virtually all phytoplankton production goes to zooplankton (Steele, 1974:5). Thus phytoplankton biomass does not accumulate. Measuring the standing biomass of phytoplankton and calculating its productivity is relatively easy. Measuring organisms of higher trophic levels is much more difficult. Productivity of higher trophic levels can be estimated by the formula (Lalli and Parsons, 1994:116-117):

$$P_T = T_E \bullet P_{T-1} \qquad (14)$$

Where T_E is the transfer efficiency between the trophic levels and P_{T-1} is the productivity in the trophic level below the one of interest. T_E is generally accepted to be 0.2 for the herbivores in marine systems (Lalli and Parsons, 1994:117). However, this efficiency is less in food abundant areas such as upwelling zones. Field data suggests a productivity of 75 mg per meter^2 per year for the Primary Consumers (Barnes and Hughes, 1988:65). This suggests a transfer efficiency of 12%, a 60% reduction.

$$T_e = \frac{P_T}{P_{T-1}}$$

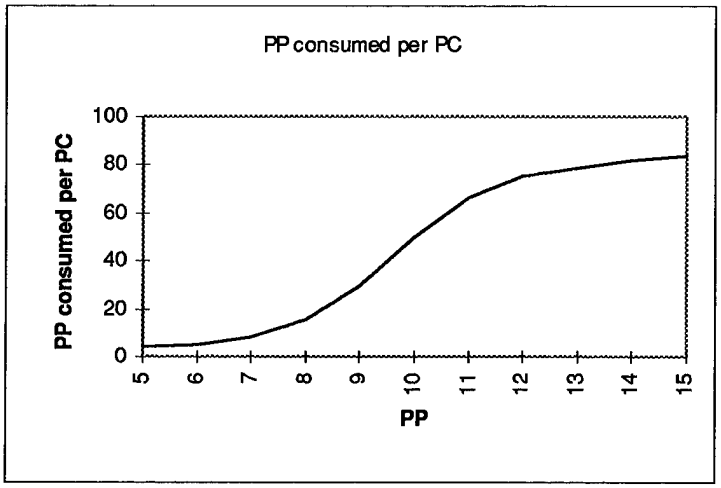
$$T_e = \frac{75(\frac{mg-of-C}{m^2-year})}{625(\frac{mg-of-C}{m^2-year})}$$

$$T_e = .12$$

Zooplankton are small, short lived organisms. The model assumes a typical life span of 2 months. This corresponds to a loss fraction of 6, the inverse of 2 out of 12

months of the year. With a loss rate equal to productivity, necessary to maintain an equilibrium biomass, this death fraction gives a standing biomass of 12.5 mg per m^2. In other words, the product of the standing biomass and the death fraction equals the productivity. This maintains a system equilibrium since net biomass is zero. A birth fraction of 6 is also necessary to give the 75 mg per m^2 per year productivity rate for the biomass.

With an average standing biomass of 12.5 mg per m^2 of Primary Consumers and 625 mg per m^2 of Primary Producers being consumed, a relationship between the Primary Consumers and the Primary Producers consumed can be established. This relationship was estimated with the function portrayed in Figure 11.



PP Consumed per PC

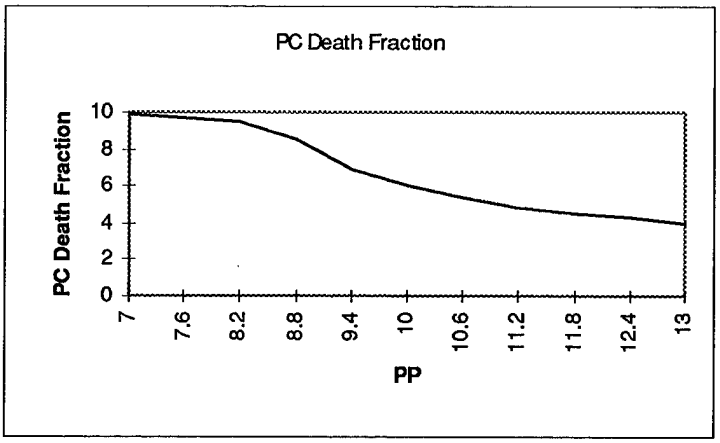
(Primary Producers (PP) are in mg per m^2. Primary Producers consumed per Primary Consumer (PC) is mg PP per mg PC per year.)

Figure 11

With an average standing biomass of Primary Producers at 10 mg per m^2, a predation rate of Primary Producers is selected to keep the system at this value such that all productivity

is utilized by the Primary Consumers. Primary Consumers in marine systems are limited by food and not predator pressure (Steele, 1974:5). Since they are starving, it is reasoned that as the food density increased, the more they would eat. Eventually, food would not be limiting and the rate of consumption would flatten out. As phytoplankton density decreases, the amount of phytoplankton consumed per herbivore could be expected to drop off, but wouldn't quite reach zero before the phytoplankton density does.

The average standing mass of 12.5 mg per m^2 of Primary Consumers, requires a Primary Consumer Death Fraction of 6 to maintain equilibrium. This Primary Consumer Death Fraction in reality is not constant, but varies with food available. A function relating the amount of food available and the death fraction of the Primary Consumers is given in Figure 12.



PC Death Fraction Vs. PP

(Primary Producers (PP) are in mg per m^2. Primary Consumer (PC) Death Fraction is dimensionless.)

Figure 12

As abundant food becomes available, the death fraction rapidly falls off until reaching some value where additional food will not extend the organism's life. For the Primary

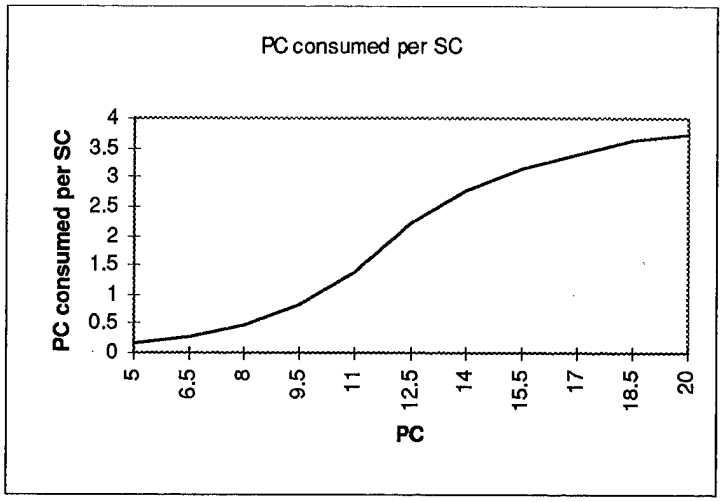
Consumers, this extended life span is assumed to be 3 months. Below the population maintenance level, the death fraction increases.

The Primary Consumers also have their lives cut short by being fed upon by the Secondary Consumers. The Secondary Consumers are primarily piscivorous fish such as tuna. Estimating the Secondary Consumer's productivity by the productivity of the Primary Consumers and Equation 14 gives:

$$P_{SC} = .09 \bullet 75(\frac{mg - of - C}{m^2 - year})$$

$$P_{SC} = 6.75(\frac{mg - of - C}{m^2 - year})$$

The trophic level transfer efficiency between herbivores and carnivores, T_E, is considered 0.15 (Lalli and Parsons, 1994:120). This is scaled down to 0.09 by the 60% reduction in efficiency due to the upwelling zone. An assumed life span of 5 years gives a 0.2 death fraction, resulting in an average Secondary Consumer biomass of 33.75 mg per m^2. If these Secondary Consumers are the only pressure on the Primary Consumers, they would need to exert predation pressure given by the function in Figure 13 to maintain Primary Consumers at an equilibrium level.



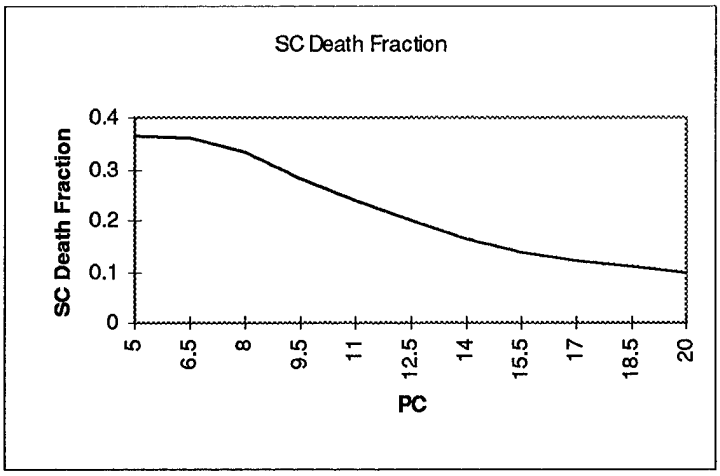
PC Consumed per SC

(Primary Consumers (PC) are in mg per m^2. Primary Consumers consumed per Secondary Consumer (SC) is mg PC per mg SC per year.)

Figure 13

This is similar to the predation curve between the Primary Producers and Primary Consumers and by itself will hold the Primary Consumers in equilibrium. Since the Primary Consumers are held in check mostly through lack of food however, the total death fraction is a composite between the two. In the model, twenty percent of the Primary Consumer's death fraction results from predators and eighty percent from the food supply of Primary Producers.

Like the Primary Consumers, the Secondary Consumers are assumed to be mostly limited by food (eighty percent of death fraction) and predation pressure from the Tertiary Consumers (twenty percent of death fraction). The death fraction from prey density is given by Figure 14.



SC Death Fraction Vs. PC

(Primary Consumers (PC) are in mg per m^2. Secondary Consumer (SC) Death Fraction is dimensionless.)

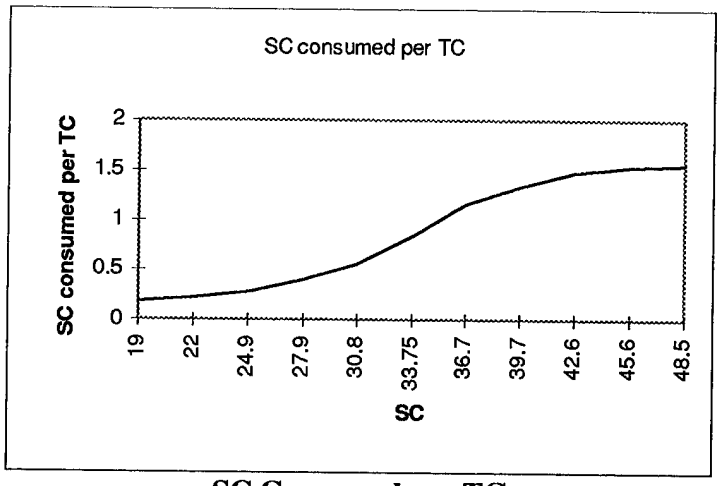
Figure 14

Predation pressure is expressed as Secondary Consumers killed per Tertiary Consumer. Tertiary Consumers are large predators such as dolphins and sharks. Calculating their productivity from the Secondary Consumers' productivity with Equation 14:

$$P_{TC} = .06 \bullet 6.75\left(\frac{mg - of - C}{m^2 - year}\right)$$

$$P_{TC} = .405\left(\frac{mg - of - C}{m^2 - year}\right)$$

The trophic level transfer efficiency between carnivores that eat herbivores and carnivores that eat other carnivores, $T_{E,}$ is considered 0.1 (Lalli and Parsons, 1994:120). Scaling down by 0.6 because of the high productivity area efficiency loss, a value of 0.06 is used. Determining the biomass of Tertiary Consumers is based upon a 20 year life span. This productivty fraction of 0.05 needs 8.1 mg per m^2 of biomass to generate the required Tertiary Consumer productivity. Tertiary Consumers prey on Secondary Consumers by Figure 15.



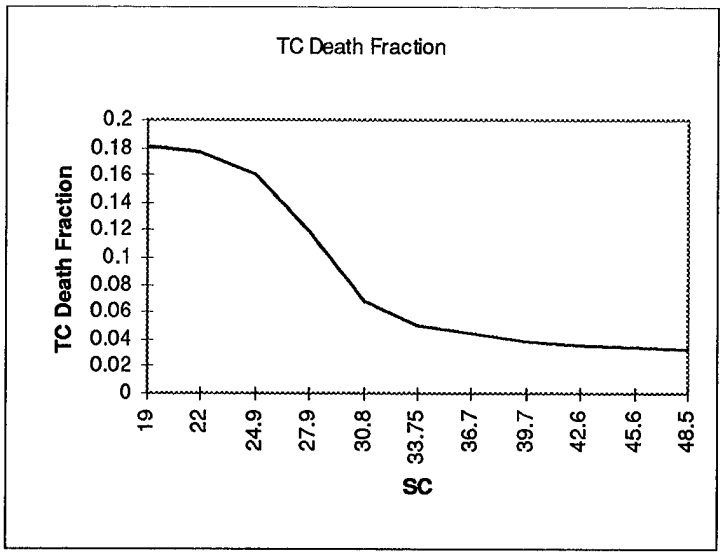
SC Consumed per TC

(Secondary Consumers (SC) are in mg per m^2. Secondary Consumers consumed per Tertiary Consumer (TC) is mg PC per mg SC per year.)

Figure 15

Such predation pressure on Secondary Consumers by Tertiary Consumers accounts for 20% of the Secondary Consumer Death Fraction, much like the case of the Secondary Consumers preying on the Primary Consumers.

A Tertiary Consumer Death Fraction of 0.05 will exist if the Secondary Consumer biomass is at the equilibrium level of 33.75 mg per m^2. A relationship between the Tertiary Consumer Death Fraction and the Secondary Consumer biomass concentration is given as Figure 16.



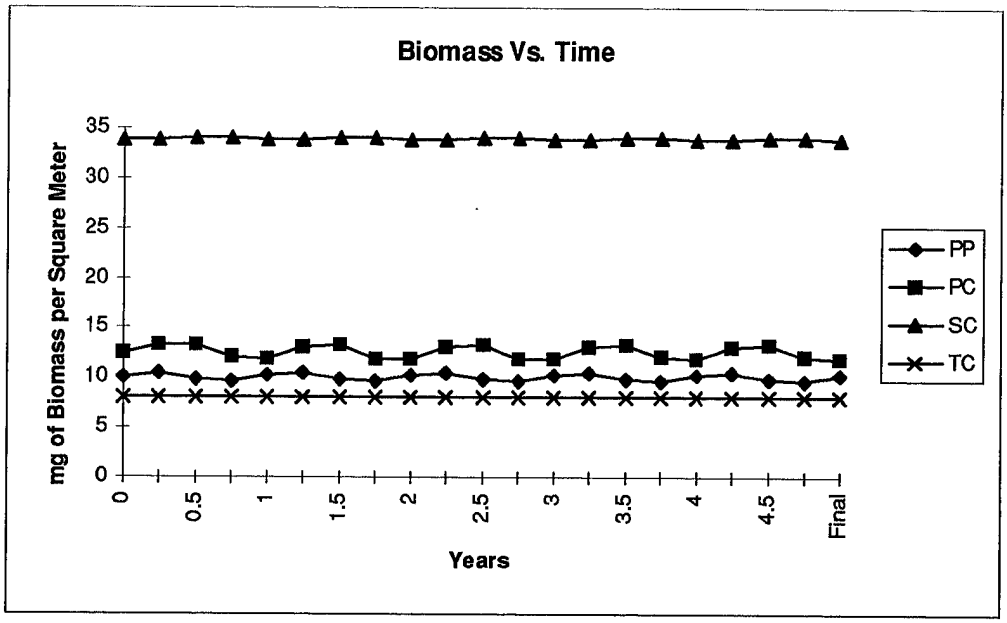
TC Death Fraction Vs. SC

(Secondary Consumers (SC) are in mg per m^2. Tertiary Consumer (TC) Death Fraction is dimensionless.)

Figure 16

Plentiful food is thought to increase Tertiary Consumers' life spans to 30 years. Tertiary Consumers have no natural enemies and are not subject to predation.

The real world is dynamic and does not maintain a steady equilibrium. Instead, biomass changes seasonally. This real world observation is modeled by the changing productivity of the Primary Producers and feedback through out the system by the relationships defined in Figures 11-16. Biomass for each trophic level is given for the model's base case for a five year period in Figure 17.



Biomass Vs. Time
Biomass is given as mg per meter^2 in the coastal region of interest.

Figure 17

Note that the Primary Producers (◆) reflect seasonal changes, but remain relatively stable. However, their changing and widely varying productivity affects the next trophic level, Primary Consumers (■), more profoundly. The oscillation is felt into the Secondary Consumers (▲), but these longer living organisms aren't as vulnerable to seasonal fluctuations and the distrurbance is dampened out. Tertiary Consumer's (✖) biomass is affected minimally by the change in seasons.

Knowing the volume of organisms at a given trophic level is necessary in order to calculate PCB concentrations at that level. Since the stocks for biomass are expressed as mg of carbon per m^2, it is necessary to convert them into cubic meters. This is done by multiplying together the biomass of the trophic level, the specific volume of carbon, and the area of the region of interest. PCB concentrations estimated by the model are

conservative since the volume of the organisms is smaller than in reality. The total volume of piscivorous fishes' (Secondary Consumers) average biomass is:

$$V_{SC} = 33.75(\frac{mg-of-C}{m^2}) \bullet \frac{1}{2.26 \bullet 10^9}(\frac{m^3}{mg-of-C}) \bullet 46{,}300(m) \bullet 92{,}600(m) \qquad (15)$$

$$V_{SC} = 64.03(m^3)$$

The model recalculates the volume of all trophic levels every time step.

PCBs enter the food chain at the lowest levels through partitioning. This effects both the Primary Producer and Primary Consumer animals. These small organisms have large amounts of surface area relative to internal volume. Such animals have partitioning as the dominant pathway for PCB uptake (Spacie, A. and others, 1995:508-509). This uptake is approximated by using the octanol-water partition coefficient (Covello and Merkhoffer, 1993:114):

$$\frac{C_{PREY}}{C_{CW}} = K_{LOW} = 10^6 \qquad (16)$$

$$\frac{C_{PREY}}{C_{CW}} = K_{HOW} = 10^7 \qquad (17)$$

K_{LOW} is the octanol-water partition coefficient for LPCBs and K_{HOW} is the octanol-water partition coefficient for HPCBs. HPCBs have a higher value since the octanol-water partition coefficient increases with chlorination (Bright and others, 1996:2504). C_{PREY} is in grams of PCB per meter^3 of organism and is calculated separately for both LPCBs and HPCBs. Although Primary Producers uptake PCB material through partitioning, this is not magnified by the Primary Consumers as the Primary Consumers are small enough to

partition any excess PCBs back into the water through gill excretion (Spacie, A. and others, 1995:508-509;Connolly, 1991:763). PCBs in the bodies of Primary Producers are not available to Primary Consumers through partitioning.

Carnivores consume prey for metabolic purposes. The Tertiary and Secondary Consumer animals are much larger than the zooplankton and phytoplankton of the first two trophic levels and have a smaller surface area compared to their internal volume. Their skin keeps nutrients (N, P, etc.) inside their bodies in concentrations far greater than the surrounding water (Spacie and others, 1995: 514; Bright and others, 1996:2507). The dominant pathway for their PCB uptake is consumption of contaminated prey (Vassilopoulou and others, 1993: 287; Jackson and Schindler, 1996:1861). The model dismisses a partitioning pathway of PCB uptake as insignificant for Tertiary and Secondary Consumers. The equation for predation uptake is:

$$PU_{1,2} = M_{Prey} \bullet C_{PCB-Prey} \bullet \gamma \qquad (18)$$

Where M_{Prey} is the mass of prey being consumed by the predator and $C_{PCB\text{-}PREY}$ is the PCB concentration within the prey. γ is the PCB uptake factor which is around 0.55 (Jackson and Schindler, 1996:1863-1864). For HPCBs, the model uses γ of 0.45 since evidence suggests that HPCBs are not as readily absorbed by the intestines as LPCBs are (Colombo and others, 1995:926). Because of this difference, uptake rates are calculated separately for LPCBs and HPCBs. In the model, the term Predation 1 refers to the transfer of PCBs from Primary Consumers to Secondary Consumers. The prey terms are the mass and PCB concentration inside the Primary Consumers. Predation 2 is the

transfer from Secondary Consumers to Tertiary Consumers. In this case, Secondary Consumers are treated as the prey animal in the equation.

PCBs return to the Coastal Water compartment from organisms in three different ways. The first is partitioning, which only affects the first two trophic levels and has previously been defined. Second, an organism killed by a predator will return some PCBs to the Coastal Water compartment since not all PCBs are absorbed by the predator. Finally, organisms that perish because of low prey density will also return PCBs to the Coastal Water stock where they are again available for partitioning and dispersion.

PCBs returning to the Coastal Water stock because of predation is calculated from the equation:

$$PK_{1,2} = M_{Prey} \bullet C_{PCB-Prey} \bullet (1-\gamma) \qquad (19)$$

Grams of PCBs per year by prey killed, or *PK*, is closely related to the predation equation. Rather than multiplying by the PCB uptake factor, γ, the complement representing the proportion of PCBs not absorbed is used. PK_1 refers to the deaths of Primary Consumers by Secondary Consumer predation and PK_2 refers to the deaths of Secondary Consumers by Tertiary Consumer predation.

Flow of PCBs from organisms back to Coastal Water because of insufficient prey is given by:

$$D_{TC,SC,PC} = M_{TC,SC,PC} \bullet C_{PCB_{TC,SC,PC}} \qquad (20)$$

D denotes the PCB return rate in grams of PCB per year to the Coastal Water from marine organisms dying from insufficient prey density for Tertiary, Secondary, and

Primary Consumers. M is the mass of Tertiary, Secondary, or Primary Consumers that are dying in grams of biomass per year as a result of insufficient prey. C_{PCB} is the concentration of PCBs in grams per meter^3 in the Tertiary, Secondary, or Primary Consumers that died. LPCB and HPCB movement from death is calculated separately.

The Tertiary and Secondary Consumers are larger animals with longer life spans than the other organisms. They are considered capable of migrating away from the area of interest and taking their accumulated PCBs with them. Any such animal that does so is assumed to be instantaneously replaced by an identical animal that is PCB free. This is modeled with an expected residence time in the coastal area of interest given by:

$$Rate_{MIGRATION} = \frac{M_{PCB-SC,TC}(grams)}{Time_{RESIDENCE}(years)} \qquad (21)$$

$M_{PCB\text{-}SC,TC}$ is the mass of PCBs in the Secondary Consumers or Tertiary Consumers. $Time_{RESIDENCE}$ is assumed to be 0.2 years and is reduced to 0.05 years during storms. Outflow rates of PCBs due to migration is defined separately for LPCBs and HPCBs. The initial model used the same residence time for both Tertiary and Secondary Consumers.

Data Collection

The primary metric of interest in the model is the accumulation of PCBs in the top two trophic levels. These animals are consumed in large quantities by humans, such as tuna, or are politically sensitive, such as dolphins. At a level of 2 ppm, sea food is considered unsafe for human consumption (Richer and others, 1994:12). By varying parameters across reasonable ranges, a determination of the maximum reasonable

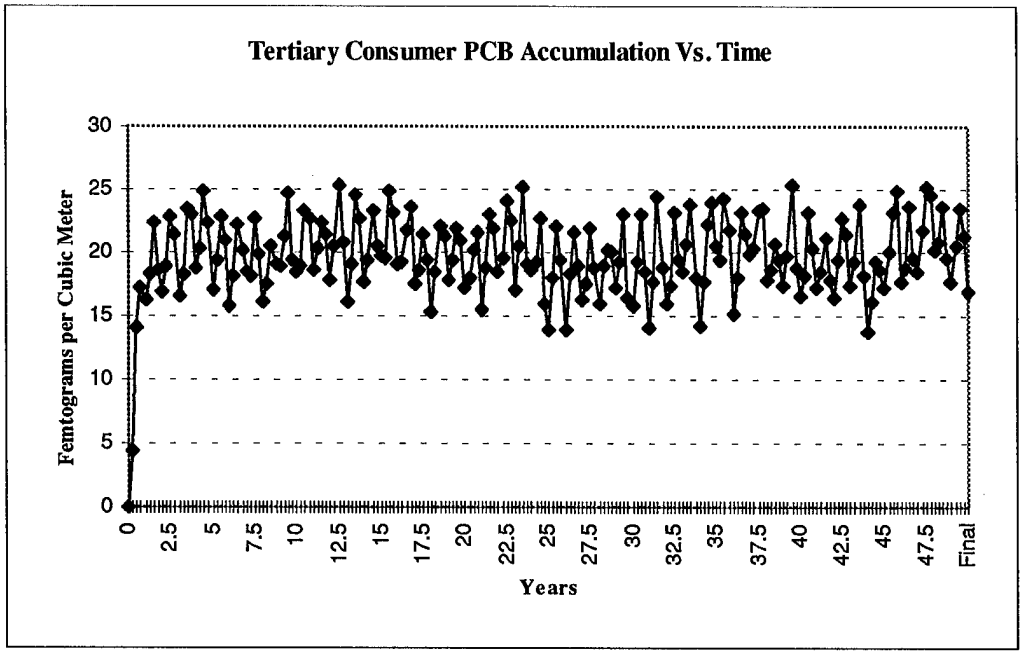
accumulation of PCBs in predators can be made. Parameters that result in considerable differences in predator accumulation can guide future laboratory research. The parameters being studied are: the release rate, vertical upwelling velocity, storm velocity, sediment transport, aerobic degradation, anaerobic degradation, PCB uptake efficiency, SC residence time (as refers to migration), TC residence time (as refers to migration), K_{SW}, K_{OW}, and Tertiary Consumer life span.

Data runs will be conducted over a 50 year simulation period with the concentration in Secondary Consumers and Tertiary Consumers recorded every 0.25 years. A time step of 0.0025 is used for the simulation algorithm. In order to make the storms reproducible, the random number seed of 1 is used. Data will be exported from STELLA II to an EXCEL spread sheet where the transient period will be truncated and an average calculated. This average is considered the equilibrium output for that run. Groups of runs will be plotted together Vs. the changing parameter to look for statistical trends.

IV. Results

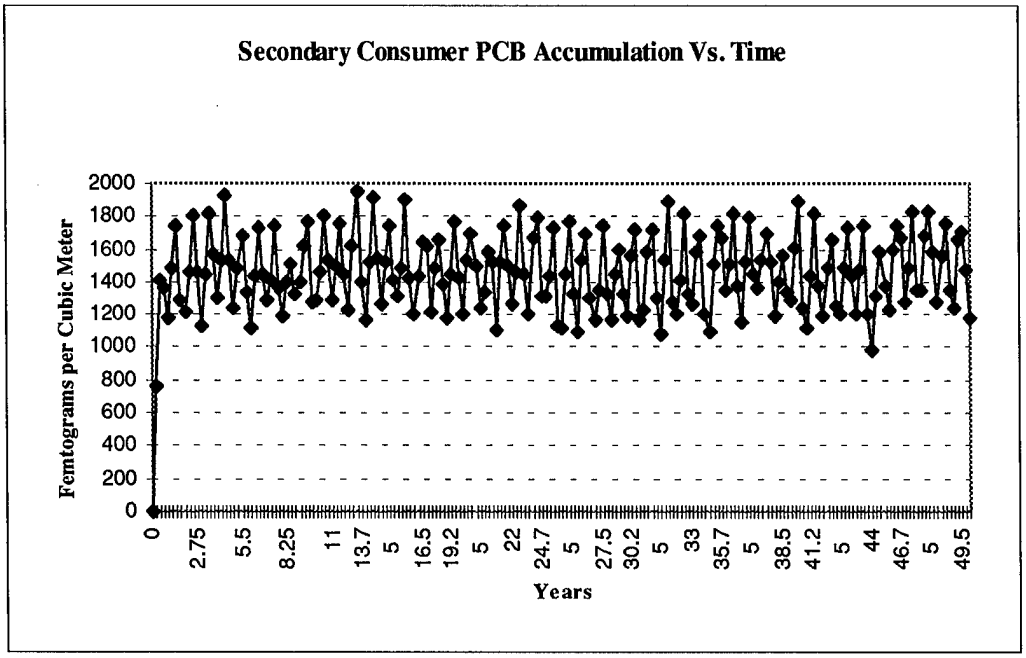
Base Case

In the base case model, trophic levels rapidly reached an equilibrium level. This indicates that it is the release rate from the wreck rather than the amount of PCBs aboard that determines accumulation in organisms. A heavier PCB load prolongs the equilibrium conditions. Secondary Consumers accumulate higher concentrations of PCBs than Tertiary Consumers in this scenario. This is attributed to biological migration and is discussed under residence time. Base case results are shown in Figures 18 and 19. The Terriary Consumers average a PCB concentration of 15.565 femtograms per cubic meter and the Secondary Consumers average a PCB concentration of 1180.56 femtograms per cubic meter.



Tertiary Consumer PCB Accumulation Vs. Time

Figure 18



Secondary Consumer PCB Accumulation Vs. Time

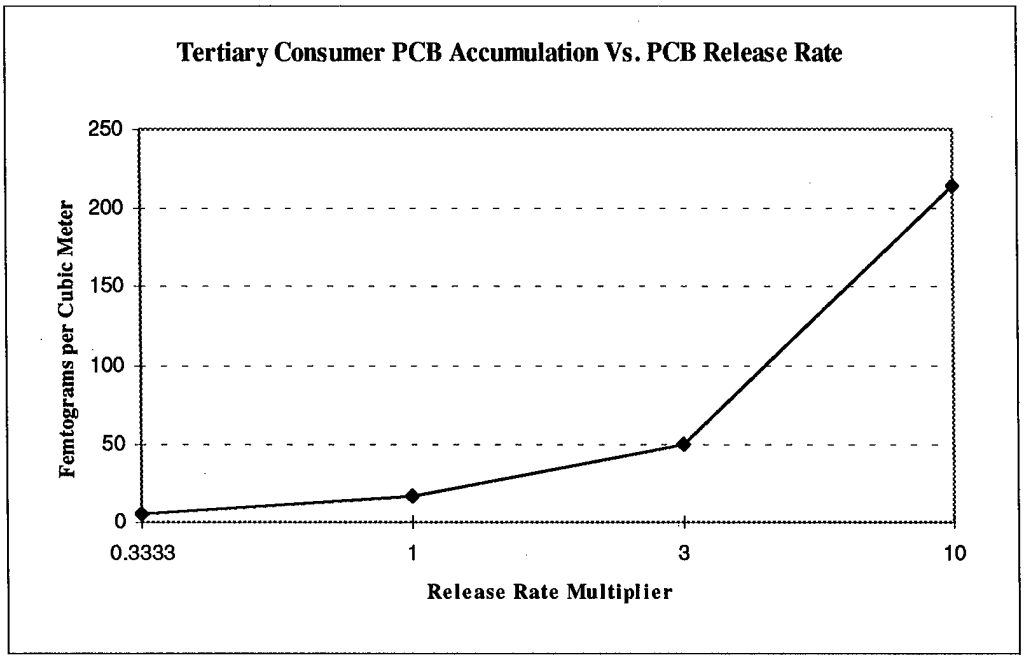
Figure 19

Sensitivity Analysis

Key to determining the accumulation of PCBs in Tertiary and Secondary consumers is the amount of PCBs available in the coastal water system to be biomagnified. Starting the chain of events is the release rate of PCBs from the wreck. This is followed by the vertical velocity of the upwelling which moves these PCBs from deep water to coastal water. The water's ability to transport PCB containing sediment is also of prime interest.

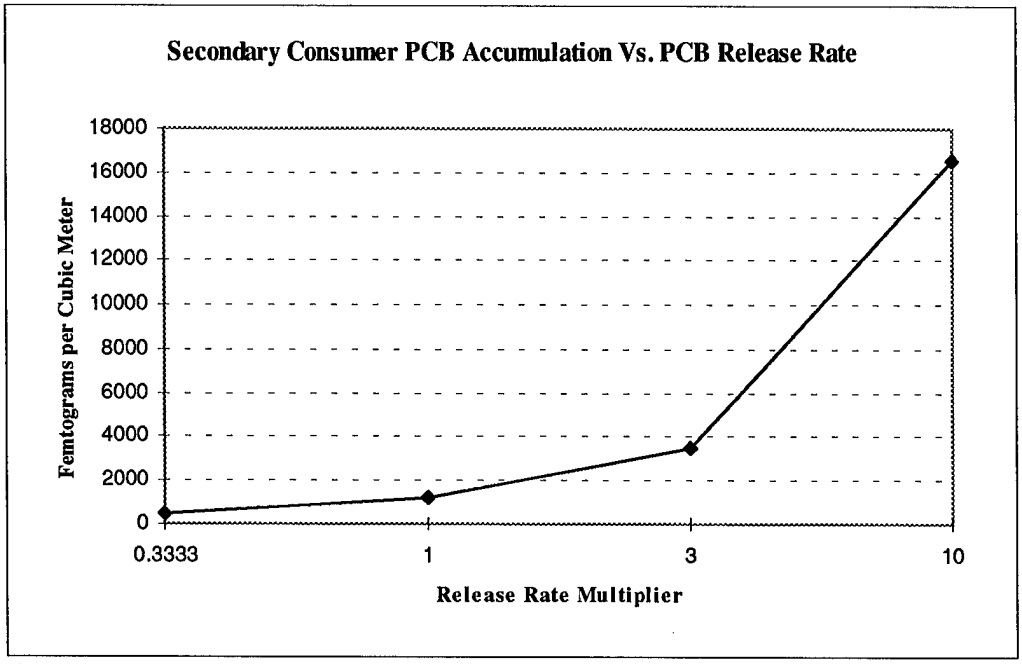
Release Rate. The original release rate determined under laboratory conditions was varied from one third to ten times its value. This original release rate of 0.058 g day^{-1} was considered conservative because of ocean temperatures (Richter and others, 1994:9).

As can be seen from Figures 20 and 21, a higher release rate results in a higher accumulation for both Tertiary and Secondary consumers. At 10 times the release rate, the highest accumulation is 16,574.66 femtograms per meter^3.



Tertiary Consumer PCB Accumulation Vs. PCB Release Rate Multiplier

Figure 20



Secondary Consumer PCB Accumulation Vs. PCB Release Rate Multiplier

Figure 21

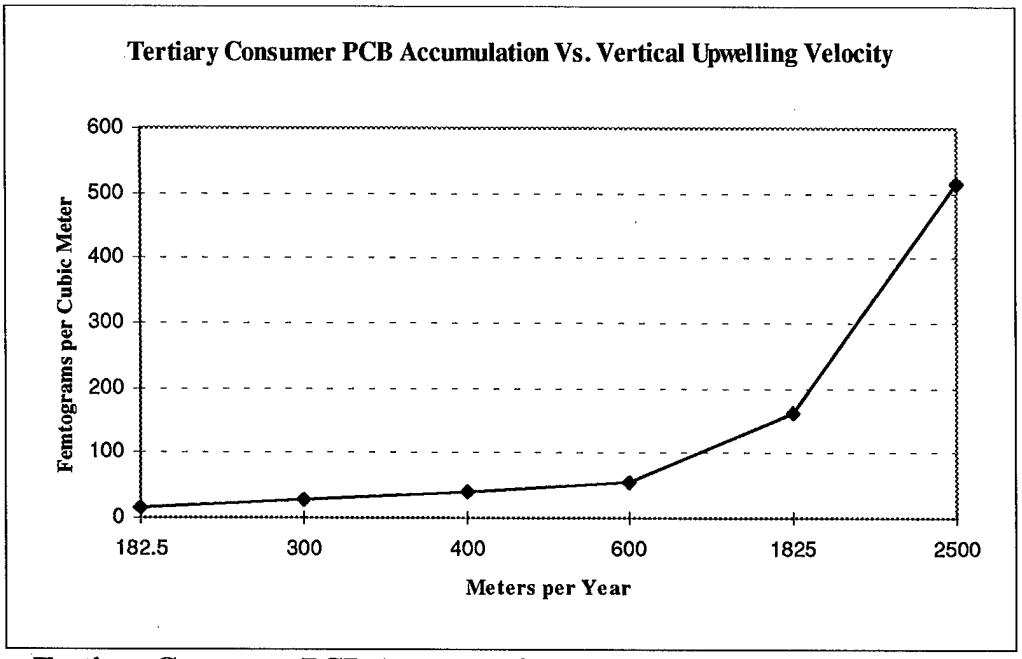
Transport Medium. The transport from the Deep to the Coastal module occurred by the physical process of upwelling water and sediment. Despite partitioning which favors a concentration in the sediment a thousand times greater than the concentration in water, water greatly dominates as the transport path for both LPCBs and HPCBs. The transport of HPCBs is much higher than that of LPCBs since there are more HPCBs in the system. Average mass transfers in grams of PCB per year are listed in Table 1.

	LPCBs	**HPCBs**
Water Upwelling	$1{,}683.65 \times 10^{-6}$	$7{,}556.81 \times 10^{-6}$
Sediment Upwelling	4.19×10^{-15}	33.00×10^{-15}

Water and Sediment Upwelling Transport Rates in Grams per Year for Lightly Chlorinated (LPCBs) and Heavily Chlorinated (HPCBs) PCBs.

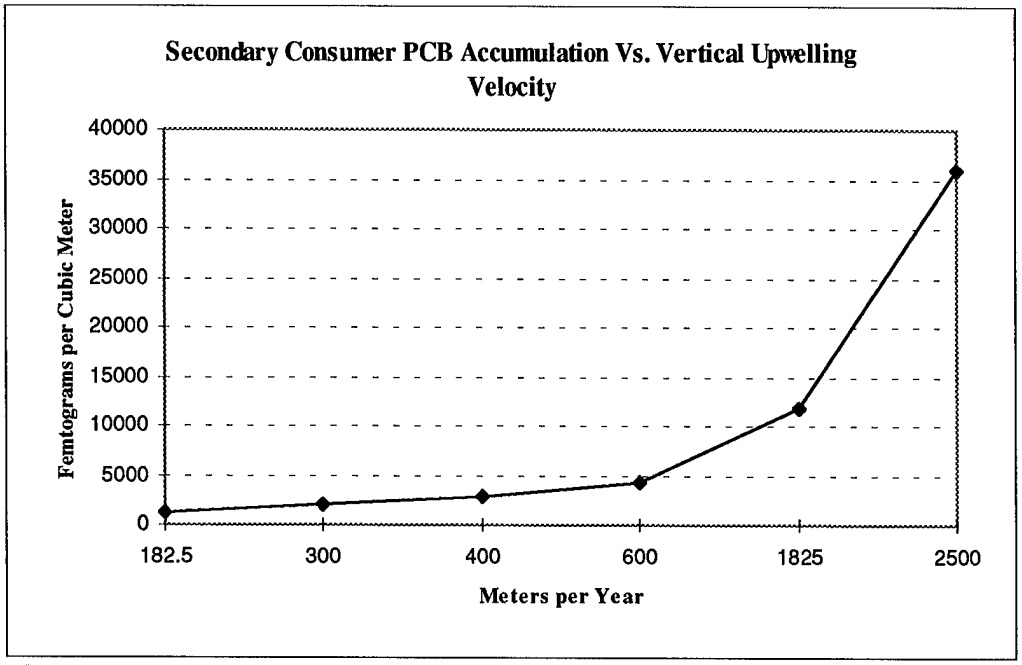
Table 1

Upwelling Velocity. Also affecting the PCBs available for bioaccumulation is the vertical velocity of the upwelling water. This appears to be a significant parameter since increases in velocity result in higher PCB accumulations for marine organisms. Speeds given on Figures 22 and 23 are for regular conditions; storm velocities are assumed to be double. With an upwelling velocity an order of magnitude greater than that found in the literature, the worst accumulation is for the Secondary Consumers and is 11,909.67 femtograms per meter^3.



Tertiary Consumer PCB Accumulation Vs. Vertical Upwelling Velocity

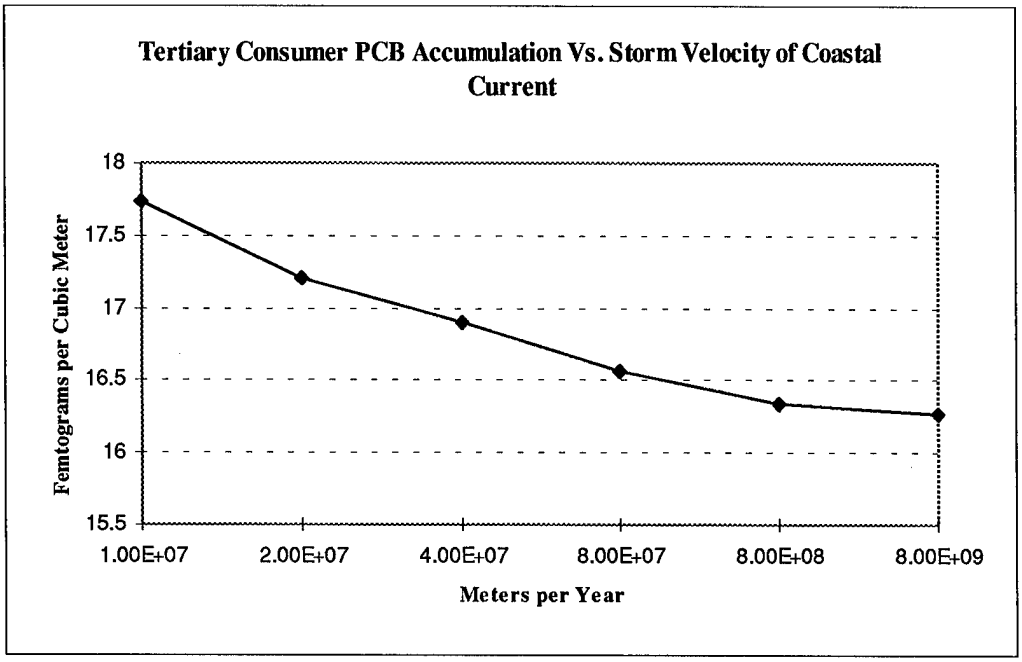
Figure 22



Secondary Consumer PCB Accumulation Vs. Vertical Upwelling Velocity

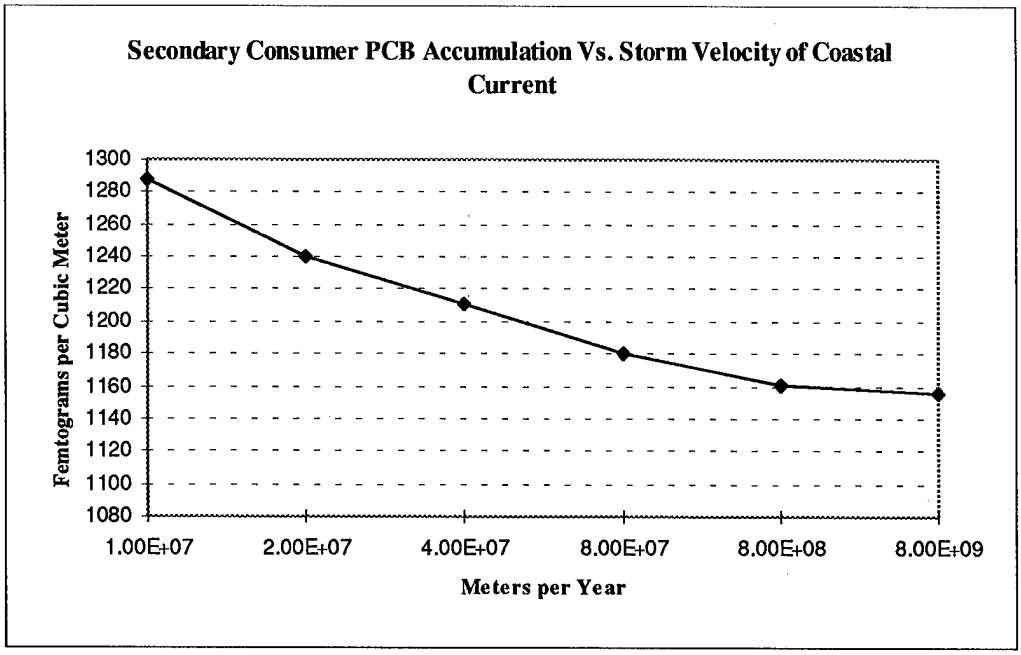
Figure 23

Storm Velocity. The coastal current increases under storm conditions. How much effect this storm velocity had on the behavior of the system is presented as Figures 24 and 25. As the storm velocity of the coastal current increases, less accumulation results. This occurs from an increase in the mass of PCBs being dispersed out to sea. Despite an increase in coastal current storm velocity over 3 orders of magnitude, accumulation does not decrease dramatically.



Tertiary Consumer PCB Accumulation Vs. Storm Velocity of Coastal Current

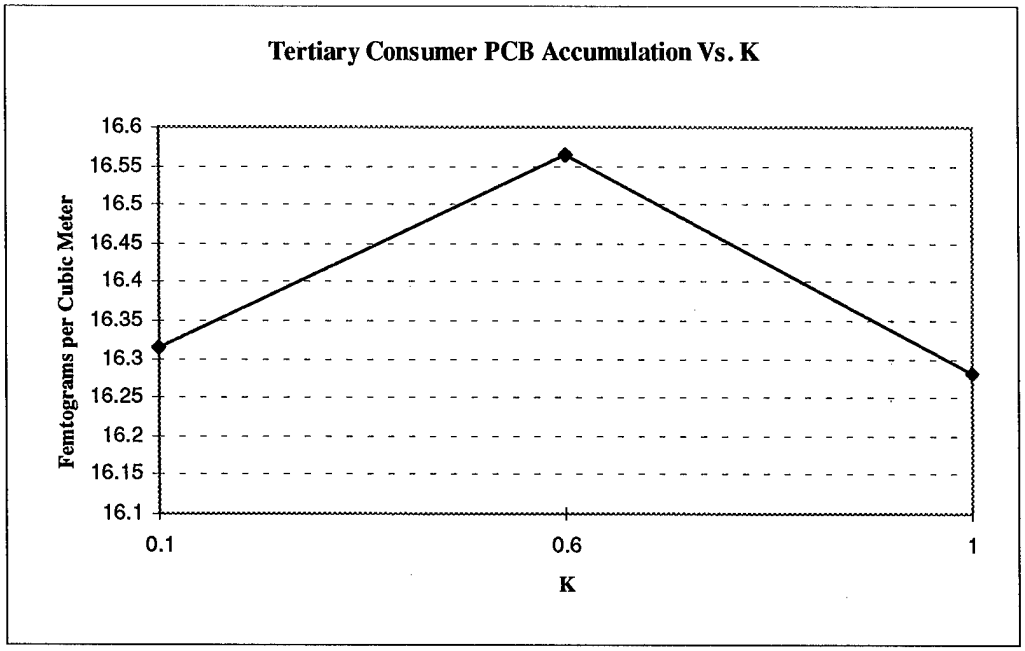
Figure 24



Secondary Consumer PCB Accumulation Vs. Storm Velocity of Coastal Current

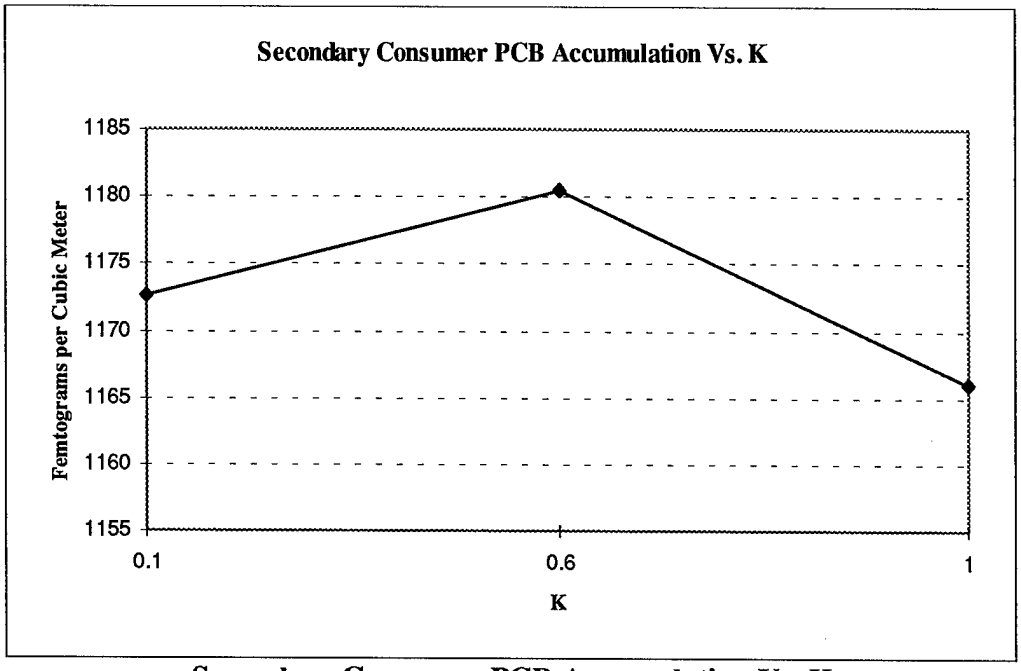
Figure 25

Sediment Transport. The ability of the water to transport sediment is expressed with the parameter *K* that must be less than unity. PCBs transported by sediment don't appear to play the role that PCBs in the water do when it comes to biological accumulation. The relationship is also not a simple one. Increasing K from 0 (where the water has zero ability to transport sediment) results in an increased accumulation. As K approaches 1, accumulation declines. This is thought to occur because of the Coastal module's larger water column width and higher sediment velocity ridding itself of PCBs through sediment deportation faster than PCBs can enter the module by sediment upwelling. Variance in accumulation from the water's ability to transport sediment is relatively small compared to other parameters as seen in Figures 26 and 27.



Tertiary Consumer PCB Accumulation Vs. K

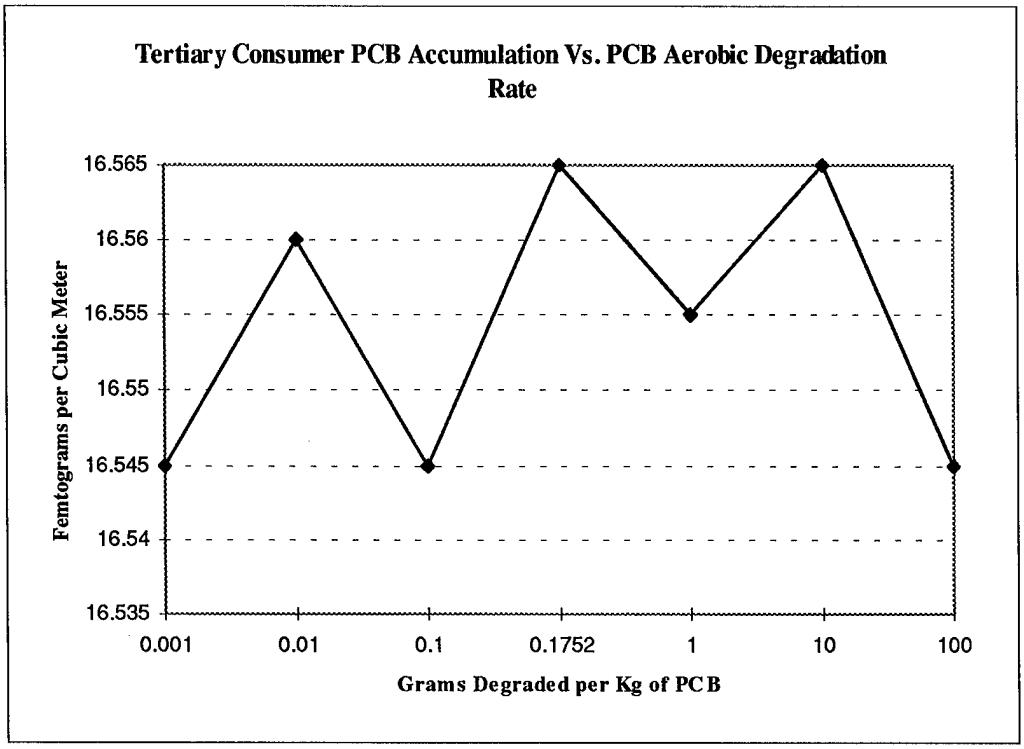
Figure 26



Secondary Consumer PCB Accumulation Vs. K

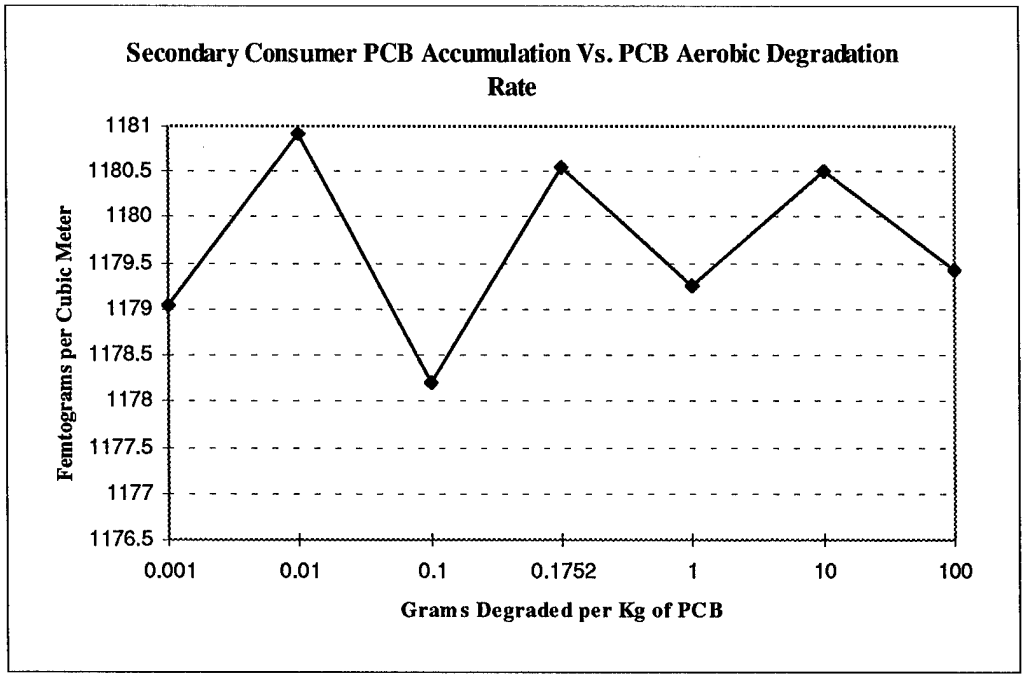
Figure 27

Aerobic Degradation. Another factor of interest in the behavior of the system is biodegradation. Biodegradation had no discernible effect on the system when it came to accumulation in marine organisms. Despite the aerobic degradation rate being varied over a range that spans five orders of magnitude, a single factor ANOVA at a significance level of α=0.05 was unable to reject the hypothesis that all runs were conducted under the same conditions. The value of $f = 0.000446$ for the Tertiary Consumers and the value of $f =$ 0.000264 for the Secondary Consumers are well below the f critical value of 2.1 at the α=0.05 significance level. The equilibrium concentration in Tertiary and Secondary Consumers is plotted versus the aerobic degradation rate in Figures 28 and 29.



Tertiary Consumer PCB Accumulation Vs. PCB Aerobic Degradation Rate

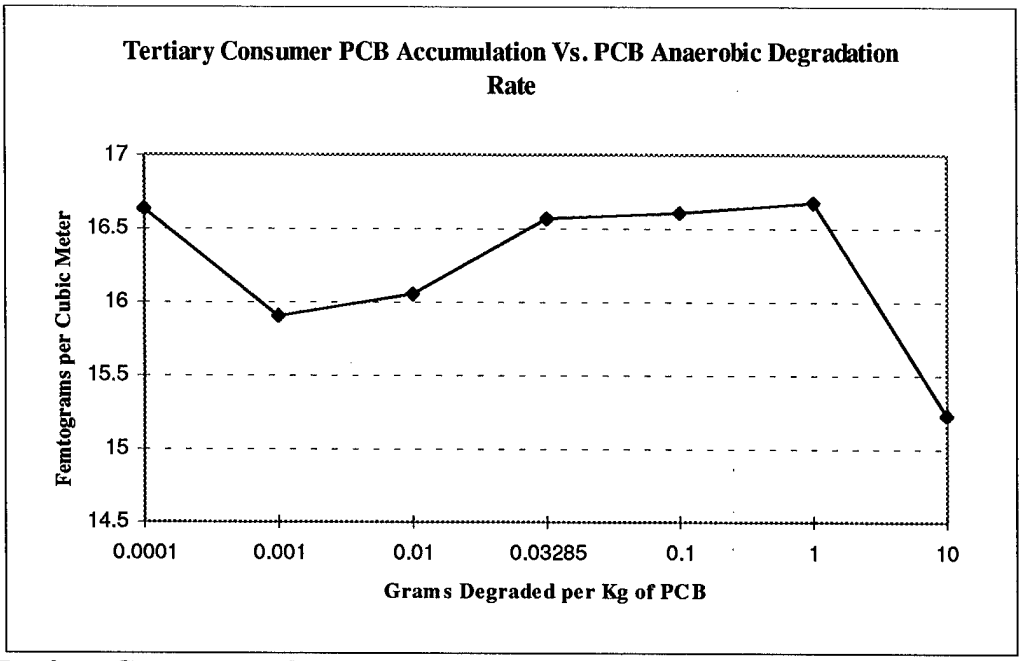
Figure 28



Secondary Consumer PCB Accumulation Vs. PCB Aerobic Degradation Rate

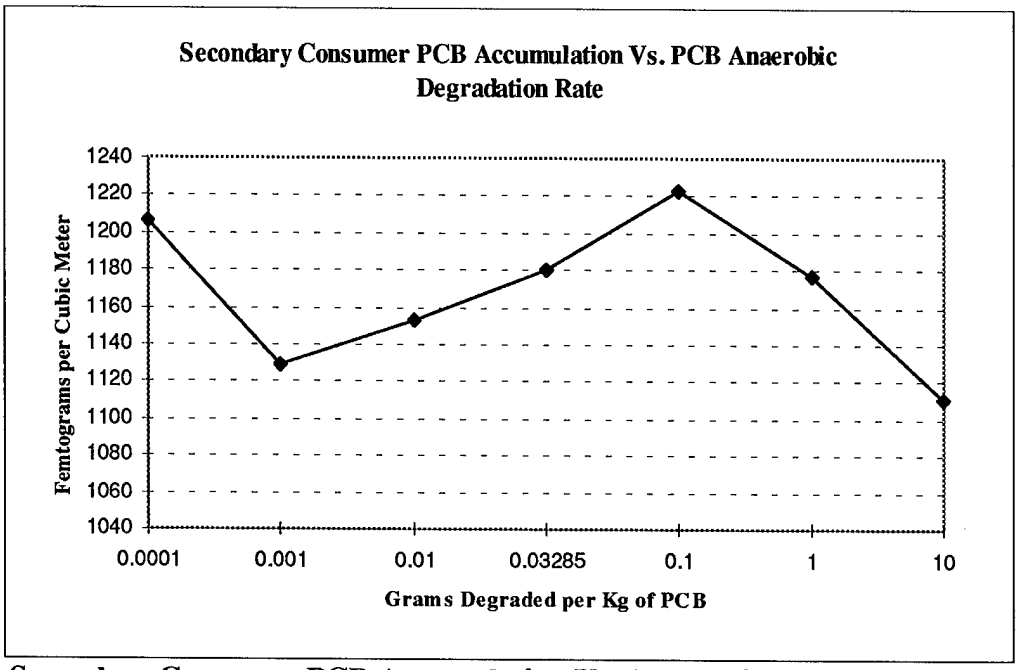
Figure 29

Anaerobic Degradation. The anaerobic degradation rate also made no significant impact on Tertiary and Secondary Consumer accumulation. The anaerobic degradation rate was varied over a range spanning five orders of magnitude. A single factor ANOVA gave Tertiary Consumer accumulation an *f* value of 0.27447 and Secondary Consumer accumulation an *f* value of 0.25004. At the significance level of α=0.05, both *f* values were well below the *f* critical = 2.1 rejection range. Accumulation in Tertiary and Secondary Consumers is plotted against the anaerobic degradation rate in Figure 30 and 31.



Tertiary Consumer PCB Accumulation Vs. PCB Anaerobic Degradation Rate

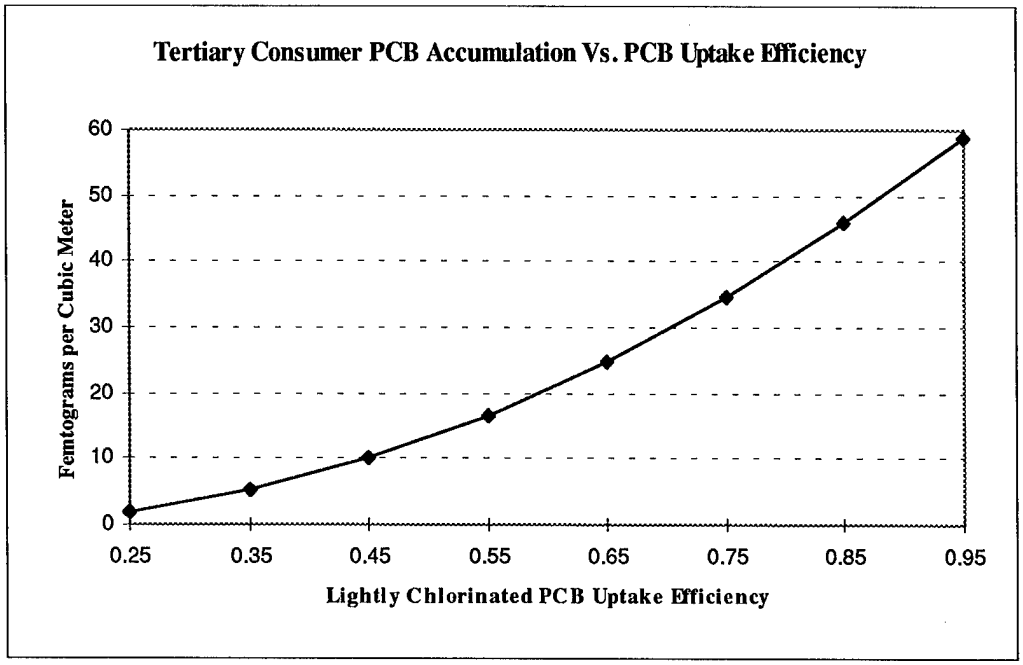
Figure 30



Secondary Consumer PCB Accumulation Vs. Anaerobic Degradation Rate

Figure 31

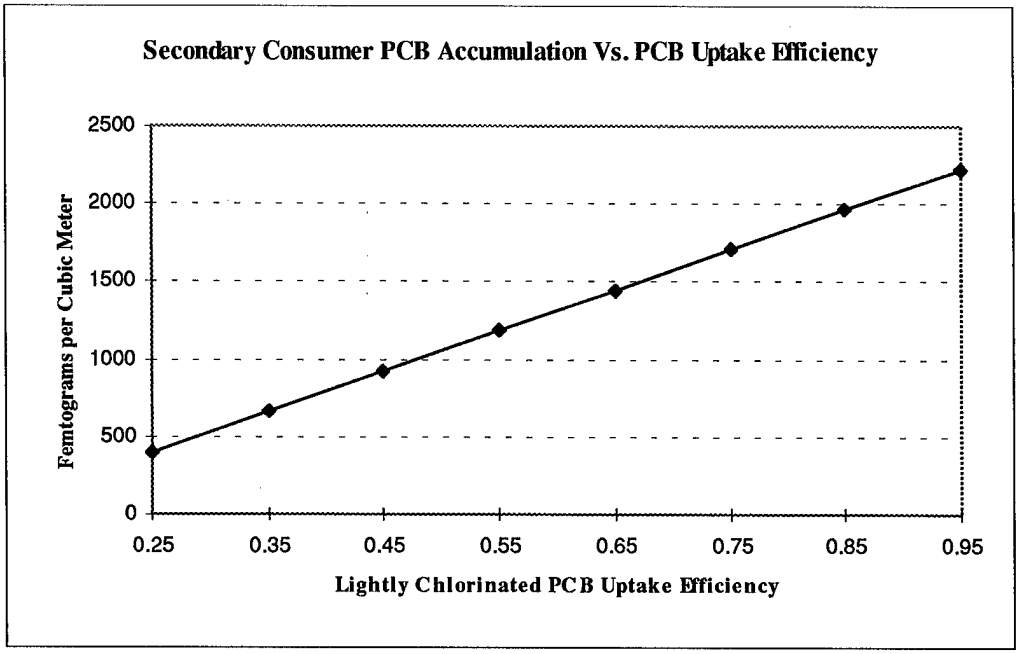
PCB Uptake Efficiency. Sensitivity analysis was also performed on the PCB uptake efficiency parameter, γ. This parameter was varied from 0.25 to 0.95 in 0.1 increments and indicates the ratio of the mass of lightly chlorinated PCBs absorbed by the predator compared to the mass of lightly chlorinated PCBs in the prey animal consumed. The PCB uptake efficiency for HPCBs is assumed to be 0.1 less than the PCB uptake efficiency for LPCBs. Results are in Figures 32 and 33.



Tertiary Consumer PCB Accumulation Vs. PCB Uptake Efficiency

(The PCB Uptake Efficiency on Figure 32 is for lightly chlorinated PCBs. The PCB Uptake Efficiency for heavily chlorinated PCBs is .1 less than the lightly chlorinated PCB Uptake Efficiency.)

Figure 32



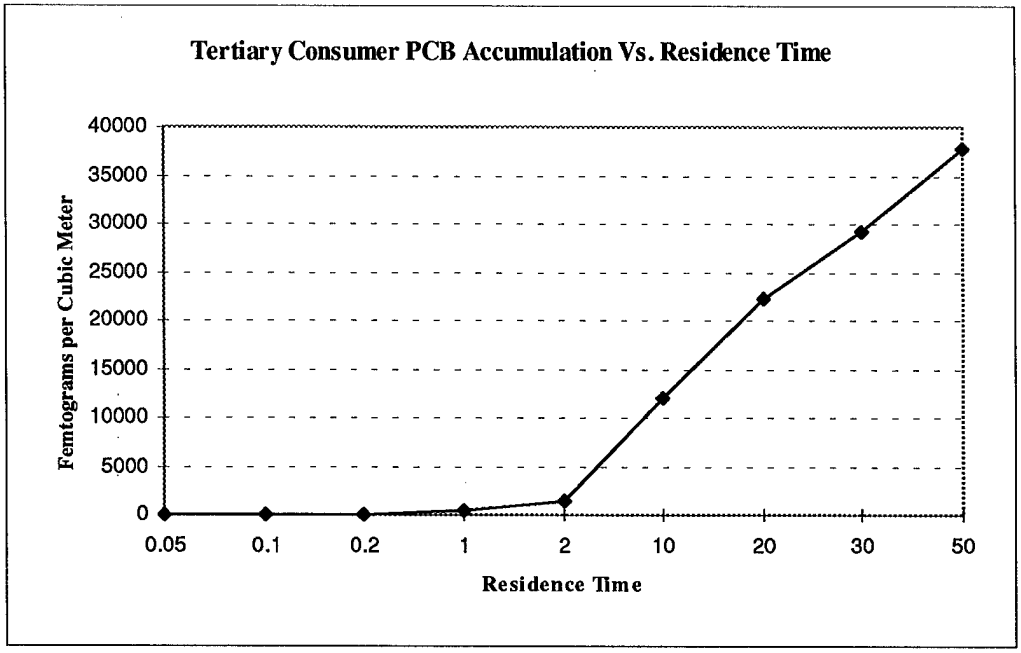
Secondary Consumer PCB Accumulation Vs. PCB Uptake Efficiency

(The PCB Uptake Efficiency on Figure 33 is for lightly chlorinated PCBs. The PCB Uptake Efficiency for heavily chlorinated PCBs is .1 less than the lightly chlorinated PCB Uptake Efficiency.)

Figure 33

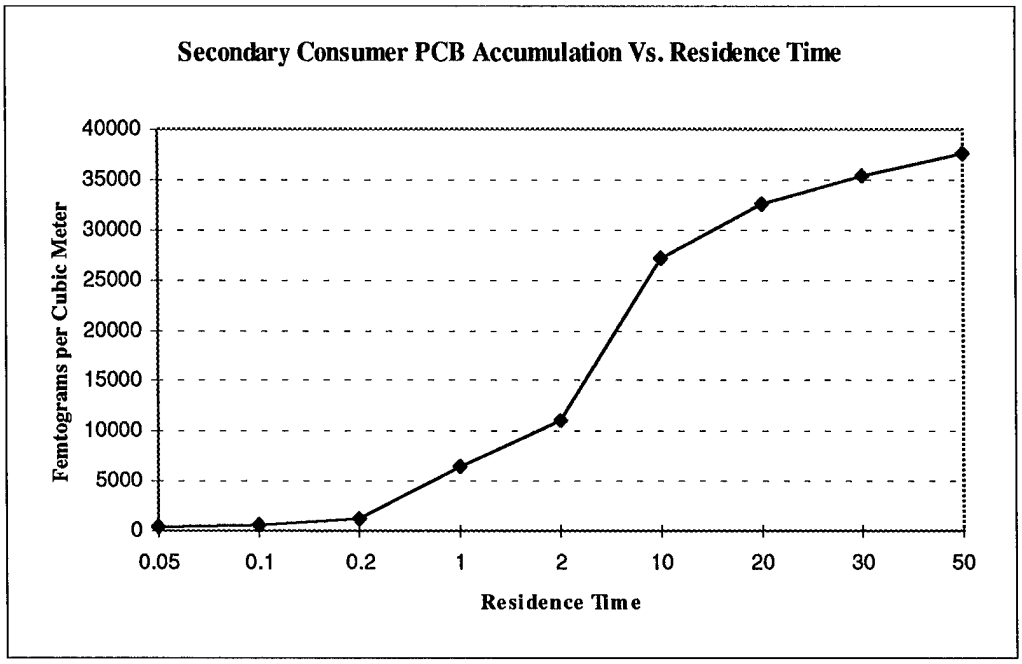
While the higher PCB uptake efficiencies result in a higher level of accumulation by marine organisms, even an uptake efficiency of 95% results in the accumulation of only 2,224.75 femtograms per cubic meter in the Secondary Consumers.

Migration. The longer a marine organism is exposed to PCBs, the greater the potential for accumulation. This was modeled with a residence time in the region of interest. Sensitivity analysis was performed from 0.05 to 50 years average residence time. Sea-lions indigenous to the area could conceivably spend their entire lives in the region of interest, while other species swim in and out. The results for accumulation in Tertiary and Secondary Consumers are in Figures 34 and 35.



Tertiary Consumer PCB Accumulation Vs. Residence Time
(The residence time for marine organisms during a storm is one quarter of the regular residence time)

Figure 34



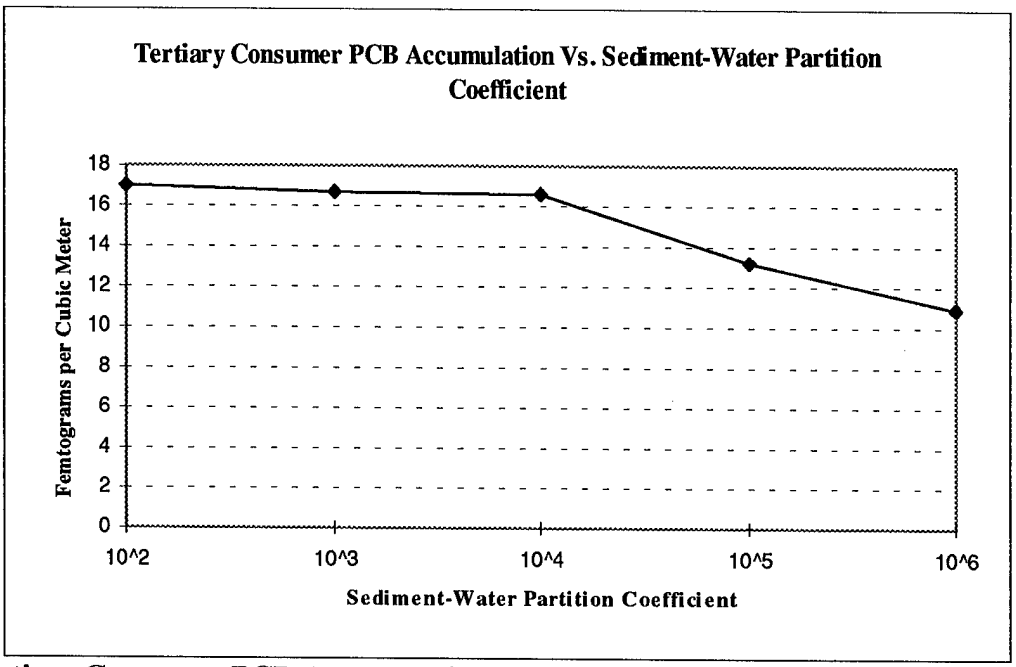
Secondary Consumer PCB Accumulation Vs. Residence Time

(The residence time for marine organisms during a storm is one quarter of the regular residence time)

Figure 35

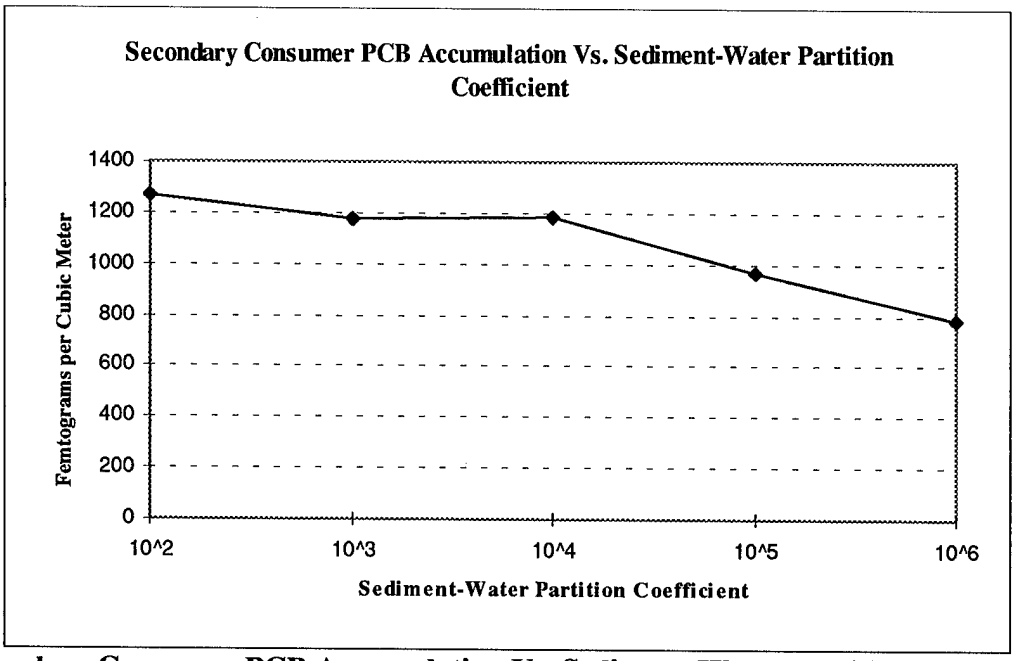
The higher the residence time, the greater the potential for PCB accumulation. When the residence time is high enough, Tertiary Consumer PCB accumulation is greater than Secondary Consumer PCB accumulation.

Sediment-Water Partition Coefficient. The higher the sediment-water partition coefficient, the more PCB material will reside in the sediment instead of in the same volume of water. These PCBs in the sediment are not as readily absorbed by marine organisms as those in the water, resulting in less accumulation overall. Decreasing biological accumulation with increasing partitioning between the sediments and water is demonstrated in Figures 36 and 37 with five runs separated by four orders of magnitude.



Tertiary Consumer PCB Accumulation Vs. Sediment-Water Partition Coefficient

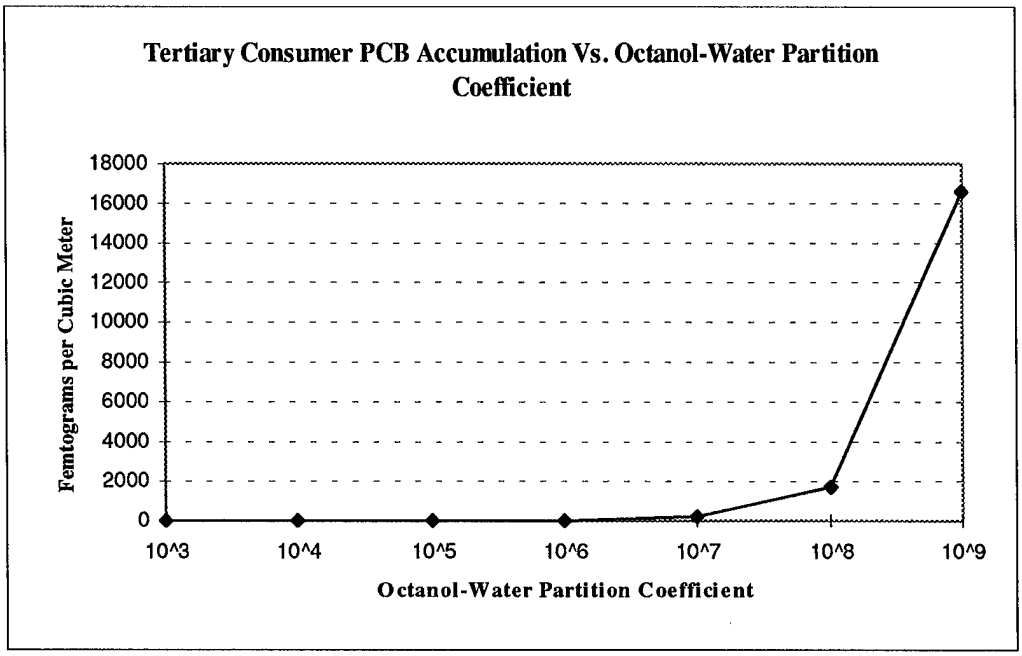
Figure 36



Secondary Consumer PCB Accumulation Vs. Sediment-Water Partition Coefficient

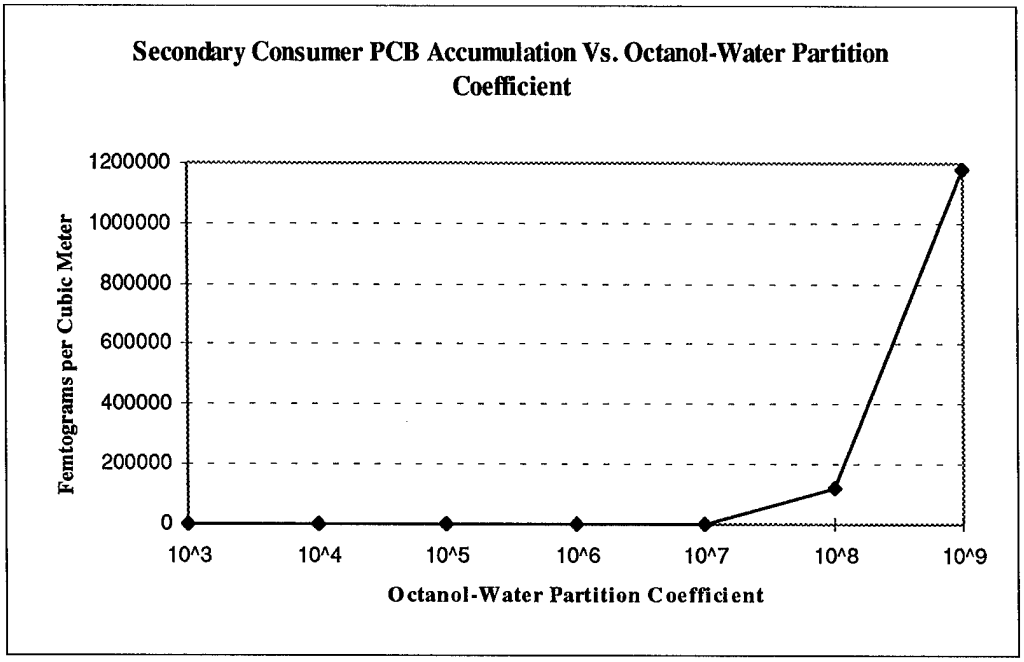
Figure 37

Octanol-Water Partition Coefficient. The octanol-water partition coefficient controls the accumulation of PCBs in the base of the food chain. As this coefficient increases, so does the PCB uptake by Tertiary and Secondary Consumers through biomagnification. Although 10^9 is two orders of magnitude greater than the highest PCB K_{OW} of 10^7, the maximum accumulation is 1,118,450 femtograms per cubic meter. The relationship is presented as Figures 38 and 39.



Tertiary Consumer PCB Accumulation Vs. Octanol-Water Partition Coefficient
(The Octanol-Water Partition Coefficient used in Figure 38 is for the lightly chlorinated PCBs. Heavily chlorinated PCBs are assumed to have a Octanol-Partition Coefficient an order of magnitude higher.)

Figure 38



Secondary Consumer PCB Accumulation Vs. Octanol-Water Partition Coefficient
(The Octanol-Water Partition Coefficient used in Figure 39 is for the lightly chlorinated PCBs. Heavily chlorinated PCBs are assumed to have a Octanol-Partition Coefficient an order of magnitude higher.)

Figure 39

Life span. Examining the Tertiary Consumer's average life span is complicated by the systems dynamic approach to calculating the standing biomass. As discussed under the methodology outlined in Chapter 3, this influences the average standing biomass of the Tertiary Consumers as well as predation on Secondary Consumers. In addition to the base case which has a Tertiary Consumer average life span of 20 years, two additional runs of 30 and 50 years were conducted. These runs showed PCB accumulation of 12.935 and 6.725 femtograms per cubic meter respectively. This decline in concentration with increasing life span is attributed to the larger amount of average standing biomass which results with organisms living longer.

Mass Conservation

Each of the 55 runs showed conservation of mass through all of the 8845 grams of PCBs in the model being accounted for.

V. Conclusion

All of the model runs show accumulation in marine organisms many orders of magnitude below the 2 ppm standard set for human consumption of seafood by the Food and Drug Administration (Richter and others, 1994:12). Potential for damage in the marine ecosystem appears to be very minimal. In addition, this study demonstrates processes of biomagnification, biodegradation, physical transport processes, and partitioning coefficients and their minimal effect on the behavior of the system.

The potential of magnification by the food chain seems limited. Tertiary Consumers did not accumulate PCB concentrations in excess of the Secondary Consumers. This is tied to the organism's ability to readily migrate to cleaner water.

Biodegradation plays a minimal role in the behavior of the system in regards to accumulation in marine organisms. PCBs in organism's bodies are not available for microorganisms to perform degradation on. This makes such degradation a long term process.

Sediment PCB transport processes are not significant compared to PCB transport by water. While PCBs partition to sediment, the constantly moving water over the sediment keeps the concentration in the water above PCB containing sediment effectively zero. The water takes PCB material from the sediment by partitioning and moves it at a much higher speed than sediment particles travel. Research on physical transport processes would be better served by concentrating on current flow and the upwelling of water rather than the movement of sediment.

Accumulation in higher marine organisms increases with increases in the octanol-water partition coefficient for both Tertiary and Secondary Consumers. Accumulation in marine organisms decreases slightly with increases in the sediment-water partition coefficient. Of the two coefficients, the octanol-water partition coefficient plays a larger role in marine organism accumulation.

Given the high costs of alternative disposal means of aging fleet assets and the minimal risk posed to the marine ecosystem by SINKEX, the use of old vessels as targets seems an economical means of disposal. Given the actual SINKEX depths that are generally much greater than the required 6000 feet, transport of sufficient concentrations of PCBs to cause ill effects seems remote.

If interested in protecting the marine ecosystem, money would be better spent on safety and navigation aids to commercial shipping. While the area off the coast of California is referred to as "low risk" in regards to accidents, 72 vessels over 100 tons had mishaps such as sinking, floundaring, or colliding in the period from 1975 to 1980 (Couper, 1983:162). These vessels were almost certainly laden with cargo and POL products rather than scrubbed clean like SINKEX vessels.

Appendix: Model Equations

[STOCK-Mass of PCBs totally degraded]

Completely_Degraded(t) = Completely_Degraded(t - dt) + (Aerobic_D + Aerobic_S) * dt
INIT Completely_Degraded = 0

Inflows:

[FLOW-g/y of LPCBs becoming completely degraded in deep water]

Aerobic_D = .1752*(LPCBs_D_Sediment/1000)

[FLOW-g/y of LPCBs becoming completely degraded in shallow (coastal water]

Aerobic_S = .1752*(LPCBs_S_Sediment/1000)

[STOCK-Total mass of PCBs that have left model by deep water physical processes]

D_Gone(t) = D_Gone(t - dt) + (L_Dispersion_D + L_Eroded_D + H_Eroded_D + H_Dispersion_D) * dt
INIT D_Gone = 0

Inflows:

[FLOW-g/y of LPCBs in deep water leaving model by current]

L_Dispersion_D = D_Water_Velocity*L_Conc_D_Water*Area_Water_Column_D

[FLOW-g/y of LPCBs in deep sediment leaving model by errosion of sediment]

L_Eroded_D = Width_DWC*L_Conc_D_Sediment*(1/Den_Sed)*V_Deep_Sed

[FLOW-g/y of HPCBs in deep sediment leaving model by errosion of sediment]

H_Eroded_D = Width_DWC*H_Conc_D_Sediment*(1/Den_Sed)*V_Deep_Sed

[FLOW-g/y of HPCBs in deep water leaving model by current]

H_Dispersion_D = D_Water_Velocity*Area_Water_Column_D*H_Conc_D_Water

[STOCK-Total mass of HPCBs in Deep Sediments]

HPCBs_D_Sediment(t) = HPCBs_D_Sediment(t - dt) + (H_Partition_D - Anaerobic_D - HPCBs_Sed_Upwell - H_Eroded_D) * dt
INIT HPCBs_D_Sediment = 0

Inflows:

[FLOW-g/y of HPCBs entering deep sediment by partitioning from deep water]

H_Partition_D = (H_Conc_D_Water*Vol_D_Sediment*HKsw)-HPCBs_D_Sediment

Outflows:

[FLOW-g/y of HPCBs becoming LPCBs from biodegradation, enters LPCBs_D_Sediment]

Anaerobic_D = .03285*(HPCBs_D_Sediment/1000)

[FLOW-g/y of HPCBs entering coastal sediments by upwelling]

HPCBs_Sed_Upwell = Width_DWC*H_Conc_D_Sediment*(1/Den_Sed)*V_Up_Sed

[FLOW-g/y of HPCBs leaving model from sediment errosion]

H_Eroded_D = Width_DWC*H_Conc_D_Sediment*(1/Den_Sed)*V_Deep_Sed

[STOCK-Total mass of HPCBs in deep water]

HPCBs_D_Water(t) = HPCBs_D_Water(t - dt) + (Release_H - H_Partition_D - Upwell_H - H_Dispersion_D) * dt

INIT HPCBs_D_Water = 0

Inflows:

[FLOW-g/y of HPCBs entering deep water from wreck]

Release_H = 17.32

Outflows:

[FLOW-g/y of HPCBs partitioning to deep sediment]

H_Partition_D = (H_Conc_D_Water*Vol_D_Sediment*HKsw)-HPCBs_D_Sediment

[FLOW-g/y of HPCBs entering coastal water by upwelling]

Upwell_H = Upwell_Velocity*H_Conc_D_Water*Area_Water_Column_D

[FLOW-g/y of HPCBs leaving model by dispersion to the depths with current]

H_Dispersion_D = D_Water_Velocity*Area_Water_Column_D*H_Conc_D_Water

[STOCK-Total mass of HPCBs aboard wreck]

HPCBs_in_Wreck(t) = HPCBs_in_Wreck(t - dt) + (- Release_H) * dt

INIT HPCBs_in_Wreck = 7236

Outflows:

[FLOW-g/y of HPCBs entering deep water from wreck]

Release_H = 17.32

[STOCK-HPCBs in Primary Consumer Marine Organisms]

HPCBs_PC(t) = HPCBs_PC(t - dt) + (H_Partition_2 - H_Pred_1 - H_PC_Death) * dt

INIT HPCBs_PC = 0

Inflows:

[FLOW-g/y of HPCBs entering primary consumers by partitioning from coastal water]

H_Partition_2 = (PC_Volume*H_Conc_S_Water*HKow)-HPCBs_PC

Outflows:

[FLOW-g/y of HPCBs leaving Primary Consumers from being absorbed by Secondary Consumers]

H_Pred_1 = PC_Eaten*H_Conc_PC*Gam_H

[FLOW-g/y of HPCBs leaving Primary Consumers from Primary Consumers Dying through starvation and predation-HPCBs returned to coastal water]

H_PC_Death = (PC_Starve*H_Conc_PC)+(PC_Eaten*H_Conc_PC*(1-Gam_H))

[STOCK-HPCBs in Primary Producer Marine Organisms]

HPCBs_PP(t) = HPCBs_PP(t - dt) + (H_Partition_3) * dt

INIT HPCBs_PP = 0

Inflows:

[FLOW-g/y of HPCBs entering Primary Producers by partitioning]

H_Partition_3 = ((H_Conc_S_Water*HKow*PP_Volume)-HPCBs_PP)

[STOCK-HPCBs in Secondary Consumer Marine Organisms]

HPCBs_SC(t) = HPCBs_SC(t - dt) + (H_Pred_1 - H_SC_Death - H_Migrate_1 - H_Pred_2) * dt

INIT HPCBs_SC = 0

Inflows:

[FLOW-g/y of HPCBs entering Secondary Consumers from eating Primary Consumers]

H_Pred_1 = PC_Eaten*H_Conc_PC*Gam_H

Outflows:

[FLOW-g/y of HPCBs leaving Secondary Consumers to coastal water from death by starvation and predators]

H_SC_Death = (SC_Starve*H_Conc_SC)+(SC_Eaten*H_Conc_SC*(1-Gam_H))

[FLOW-g/y of HPCBs leaving model from Secondary Consumer migration]

H_Migrate_1 = (HPCBs_SC/SC_Res_Time)

[FLOW-g/y of HPCBs leaving Secondary Consumers and entering Tertiary Consumers]

H_Pred_2 = SC_Eaten*H_Conc_SC*Gam_H

[STOCK-Total mass of HPCBs in shallow (coastal) sediment]

HPCBs_S_Sediment(t) = HPCBs_S_Sediment(t - dt) + (H_Partition_S + HPCBs_Sed_Upwell - Anaerobic_S - H_Eroded_S) * dt

INIT HPCBs_S_Sediment = 0

Inflows:

[FLOW-g/y of HPCBs entering coastal sediment from partitioning from coastal water]

H_Partition_S = (HKsw*H_Conc_S_Water*Vol_S_Sediment)-HPCBs_S_Sediment

[FLOW-g/y of HPCBs entering coastal sediment from upwelling from deep sediment]

HPCBs_Sed_Upwell = Width_DWC*H_Conc_D_Sediment*(1/Den_Sed)*V_Up_Sed

Outflows:

[FLOW-g/y of HPCBs entering coastal sediment as LPCBs through biodegradation]

Anaerobic_S = .03285*(HPCBs_S_Sediment/1000)

[FLOW-g/y of HPCBs leaving model through coastal sediment erosion]

H_Eroded_S = Width_CWC*(1/Den_Sed)*H_Conc_S_Sediment*V_Coast_Sed

[STOCK-Total mass of HPCBs in shallow (coastal) water]

HPCBs_S_Water(t) = HPCBs_S_Water(t - dt) + (H_PC_Death + H_SC_Death + Upwell_H + H_TC_Death - H_Partition_2 - H_Partition_S - H_Disperion_S - H_Partition_3) * dt

INIT HPCBs_S_Water = 0

Inflows:

[FLOW-g/y of HPCBs entering coastal water from death of primary consumers]

H_PC_Death = (PC_Starve*H_Conc_PC)+(PC_Eaten*H_Conc_PC*(1-Gam_H))

[FLOW-g/y of HPCBs entering coastal water from death of secondary consumers]

H_SC_Death = (SC_Starve*H_Conc_SC)+(SC_Eaten*H_Conc_SC*(1-Gam_H))

[FLOW-g/y of HPCBs entering coastal water from upwelling from deep water]

Upwell_H = Upwell_Velocity*H_Conc_D_Water*Area_Water_Column_D

[FLOW-g/y of HPCBs entering coastal water from death of tertiary consumers]

H_TC_Death = H_Conc_TC*TC_Starve

Outflows:

[FLOW-g/y of HPCBs leaving coastal water and entering primary consumer organisms by partitioning]

H_Partition_2 = (PC_Volume*H_Conc_S_Water*HKow)-HPCBs_PC

[FLOW-g/y of HPCBs leaving coastal water and entering shallow (coastal) sediment]

H_Partition_S = (HKsw*H_Conc_S_Water*Vol_S_Sediment)-HPCBs_S_Sediment

[FLOW-g/y of HPCBs leaving model from coastal water by dispersion with current to the depths]

H_Disperion_S = Area_Water_Column_S*H_Conc_S_Water*S_Water_Velocity

[FLOW-g/y of HPCBs leaving coastal water by partioning into primary producer organisms]

H_Partition_3 = ((H_Conc_S_Water*HKow*PP_Volume)-HPCBs_PP)

[STOCK-Total mass of HPCBs in Tertiary Consumer Marine Organisms]

HPCBs_TC(t) = HPCBs_TC(t - dt) + (H_Pred_2 - H_Migrate_2 - H_TC_Death) * dt

INIT HPCBs_TC = 0

Inflows:

[FLOW-g/y of HPCBs entering tertiary consumers from eating secondary consumers]

H_Pred_2 = SC_Eaten*H_Conc_SC*Gam_H

Outflows:

[FLOW-g/y of HPCBs leaving tertiary consumers and model by biological migrataion]

H_Migrate_2 = (HPCBs_TC/TC_Res_Time)

[FLOW-g/y of HPCBs entering coastal water from tertiary consumers dying]

H_TC_Death = H_Conc_TC*TC_Starve

[STOCK-Total mass of LPCBs in deep sediment]

LPCBs_D_Sediment(t) = LPCBs_D_Sediment(t - dt) + (L_Partition_D + Anaerobic_D - LPCBs_Sed_Upwell - Aerobic_D - L_Eroded_D) * dt

INIT LPCBs_D_Sediment = 0

Inflows:

[FLOW-g/y of LPCBs entering deep sediment by partioning from deep water]

L_Partition_D = (Vol_D_Sediment*L_Conc_D_Water*LKsw)-LPCBs_D_Sediment

[FLOW-g/y of LPCBs entering deep sediment from HPCBs that have biodegraded in the deep sediment]

Anaerobic_D = .03285*(HPCBs_D_Sediment/1000)

Outflows:

[FLOW-g/y of LPCBs entering coastal water from deep water by upwelling]

LPCBs_Sed_Upwell = Width_DWC*L_Conc_D_Sediment*(1/Den_Sed)*V_Up_Sed

[FLOW-g/y of LPCBs entering complete degradation by biodegradation in deep sediment]

Aerobic_D = .1752*(LPCBs_D_Sediment/1000)

[FLOW-g/y of LPCBs leaving model by deep sediment errosion (goes to gone)]

L_Eroded_D = Width_DWC*L_Conc_D_Sediment*(1/Den_Sed)*V_Deep_Sed

[STOCK-Total mass of LPCBs in deep water]

LPCBs_D_Water(t) = LPCBs_D_Water(t - dt) + (Release_L - L_Partition_D - Upwell_L - L_Dispersion_D) * dt

INIT LPCBs_D_Water = 0

Inflows:

[FLOW-g/y of LPCBs entering deep water from wreck]

Release_L = 3.85

Outflows:

[FLOW-g/y of LPCBs entering deep sediment from deep water by partitioning]

L_Partition_D = (Vol_D_Sediment*L_Conc_D_Water*LKsw)-LPCBs_D_Sediment

[FLOW-g/y of LPCBs leaving deep water for shallow water by upwelling]

Upwell_L = Upwell_Velocity*L_Conc_D_Water*Area_Water_Column_D

[FLOW-g/y of LPCBs leaving model and deep water by dispersion into depths by current]

L_Dispersion_D = D_Water_Velocity*L_Conc_D_Water*Area_Water_Column_D

[STOCK-Total mass of LPCBs on board wreck]

LPCBs_in_Wreck(t) = LPCBs_in_Wreck(t - dt) + (- Release_L) * dt

INIT LPCBs_in_Wreck = 1609

Outflows:

[FLOW-g/y of LPCBs being released wreck into deep water]

Release_L = 3.85

[STOCK-Total mass of LPCBs in Primary Consumer marine organisms]

LPCBs_PC(t) = LPCBs_PC(t - dt) + (L_Partition_2 - L_Pred_1 - L_PC_Death) * dt

INIT LPCBs_PC = 0

Inflows:

[FLOW-g/y of LPCBs entering primary consumers from coastal water by partitioning]

L_Partition_2 = ((L_Conc_S_Water*LKow*PC_Volume)-LPCBs_PC)

Outflows:

[FLOW-g/y of LPCBs entering secondary consumers by eating primary consumers]

L_Pred_1 = PC_Eaten*L_Conc_PC*Gam_L

[FLOW-g/y of LPCBs leaving primary consumers by death from starvation and predation]

L_PC_Death = (PC_Eaten*L_Conc_PC*(1-Gam_L))+(PC_Starve*L_Conc_PC)

[STOCK-Total mass of LPCBs in Primary Producer marine organisms]

LPCBs_PP(t) = LPCBs_PP(t - dt) + (L_Partition_3) * dt

INIT LPCBs_PP = 0

Inflows:

[FLOW-g/y of LPCBs entering Primary Producer organisms from coastal water]

L_Partition_3 = ((L_Conc_S_Water*LKow*PP_Volume)-LPCBs_PP)

[STOCK-Total mass of LPCBs in Secondary Consumer marine organisms]

LPCBs_SC(t) = LPCBs_SC(t - dt) + (L_Pred_1 - L_SC_Death - L_Migrate_1 - L_Pred_2) * dt

INIT LPCBs_SC = 0

Inflows:

[FLOW-g/y of LPCBs entering Secondary Consumers from eating Primary Consumers]

L_Pred_1 = PC_Eaten*L_Conc_PC*Gam_L

Outflows:

[FLOW-g/y of LPCBs leaving Secondary Consumers and entering Coastal ater from death of Secondary Consumers]

L_SC_Death = (SC_Starve*L_Conc_SC)+(SC_Eaten*L_Conc_SC*(1-Gam_L))

[FLOW-g/y of LPCBs leaving Secondary Consumers from migration]

L_Migrate_1 = (LPCBs_SC/SC_Res_Time)

[FLOW-g/y of LPCBs entering Tertiary Consumers from eating Secondary Consumers]

L_Pred_2 = SC_Eaten*L_Conc_SC*Gam_L

[STOCK-Total mass of LPCBs in shallow (coastal) sediment]

LPCBs_S_Sediment(t) = LPCBs_S_Sediment(t - dt) + (L_Partition_S + Anaerobic_S + LPCBs_Sed_Upwell - L_Eroded_S - Aerobic_S) * dt

INIT LPCBs_S_Sediment = 0

Inflows:

[FLOW-g/y of LPCBs entering Coastal Sediment from Coastal Water by partitioning]

L_Partition_S = (L_Conc_S_Water*LKsw*Vol_S_Sediment)-LPCBs_S_Sediment

[FLOW-g/y of LPCBs entering Coastal Sediment from degradation of HPCBs in Coastal Sediment]

Anaerobic_S = .03285*(HPCBs_S_Sediment/1000)

[FLOW-g/y of LPCBs entering Coastal Sediment from upwelling of deep sediment]

LPCBs_Sed_Upwell = Width_DWC*L_Conc_D_Sediment*(1/Den_Sed)*V_Up_Sed

Outflows:

[FLOW-g/y of LPCBs leaving Coastal Sediment by erroding out to the ocean depths, leaving model]

L_Eroded_S = Width_CWC*(1/Den_Sed)*L_Conc__S_Sediment*V_Coast_Sed

[FLOW-g/y of LPCBs leaving model by aerobic degradation]

Aerobic_S = .1752*(LPCBs_S_Sediment/1000)

[STOCK-Total mass of LPCBs in Tertiary Consumer marine organisms]

LPCBs_TC(t) = LPCBs_TC(t - dt) + (L_Pred_2 - L_TC_Death - L_Migrate_2) * dt

INIT LPCBs_TC = 0

Inflows:

[FLOW-g/y of LPCBs entering Tertiary Consumers from eating Secondary Consumers]

L_Pred_2 = SC_Eaten*L_Conc_SC*Gam_L

[FLOW-g/y of LPCBs leaving Tertiary Consumers from death brought on by starvation]

L_TC_Death = L_Conc_TC*TC_Starve

[FLOW-g/y of LPCBs leaving Tertiary Consumers and model by migration]

L_Migrate_2 = (LPCBs_TC/TC_Res_Time)

[STOCK-Total mass of LPCBs in Coastal (Shallow) Water]

LPCBs__S_Water(t) = LPCBs__S_Water(t - dt) + (L_SC_Death + Upwell_L + L_PC_Death + L_TC_Death - L_Partition_2 - L_Partition_S - L_Disperion_S - L_Partition_3) * dt

INIT LPCBs__S_Water = 0

Inflows:

[FLOW-g/y of LPCBs entering Coastal Water from death of Secondary Consumers]

L_SC_Death = (SC_Starve*L_Conc_SC)+(SC_Eaten*L_Conc_SC*(1-Gam_L))

[FLOW-g/y of LPCBs entering Coastal Water from upwelling water from Deep Water]

Upwell_L = Upwell_Velocity*L_Conc_D_Water*Area_Water_Column_D

[FLOW-g/y of LPCBs entering Coastal Water from death of Primary Consumers]

L_PC_Death = (PC_Eaten*L_Conc_PC*(1-Gam_L))+(PC_Starve*L_Conc_PC)

[FLOW-g/y of LPCBs entering Coastal Water from death of Tertiary Consumers]

L_TC_Death = L_Conc_TC*TC_Starve

Outflows:

[FLOW-g/y of LPCBs leaving Coastal Water by partitioning to Primary Consumers]

L_Partition_2 = ((L_Conc_S_Water*LKow*PC_Volume)-LPCBs_PC)

[FLOW-g/y of LPCBs leaving Coastal Water by partitioning to Coastal (Shallow) Sediment]

L_Partition_S = (L_Conc_S_Water*LKsw*Vol_S_Sediment)-LPCBs_S_Sediment

[FLOW-g/y of LPCBs leaving Coastal Water and model from current flow out to the ocean]

L_Disperion_S = Area_Water_Column_S*L_Conc_S_Water*S_Water_Velocity

[FLOW-g/y of LPCBs leaving Coastal Water by partitioning to Primary Producer Animals]

L_Partition_3 = ((L_Conc_S_Water*LKow*PP_Volume)-LPCBs_PP)

[STOCK-mg of C per m^2 of primary consumer biomass]

PC(t) = PC(t - dt) + (PC_Births - PC_Deaths) * dt

INIT PC = 12.5

Inflows:

[FLOW-mg/y of Primary Consumers Born]

PC_Births = PC*PC_Birth_Frav

Outflows:

[Flow-mg/y of Primary Consumers Dying]

PC_Deaths = (.8*PC_Death_Frac*PC)+(.2*PC_killed_per_SC*SC)

[STOCK-mg of C per m^2 of Primary Producer biomass]

PP(t) = PP(t - dt) + (PP_Births - PP_Deaths) * dt

INIT PP = 10

Inflows:

[FLOW-mg/y of Primary Producer Born]

PP_Births = PP*PP_Birth_Frac

Outflows:

[Flow-mg/y of Primary Producers Dying]

PP_Deaths = PC*PP_killed_per_PC

[STOCK-mg of C per m^2 of Secondary Consumer biomass]

SC(t) = SC(t - dt) + (SC_Births - SC_Deaths) * dt

INIT SC = 33.75

Inflows:

[FLOW-mg/y of Secondary Consumers Born]

SC_Births = SC*SC_Birth_Frac

Outflows:

[Flow-mg/y of Secondary Consumers Dying]

SC_Deaths = (.8*SC_Death_Frac*SC)+(.2*SC_killed_per_TC*TC)

[STOCK-Total grams of PCBs that have left model by migration of marine organisms]

Swam_Away(t) = Swam_Away(t - dt) + (L_Migrate_1 + H_Migrate_1 + L_Migrate_2 + H_Migrate_2) * dt

INIT Swam_Away = 0

Inflows:

[FLOW-g/y of LPCBs leaving model by migration of Secondary Consumers]

L_Migrate_1 = (LPCBs_SC/SC_Res_Time)

[FLOW-g/y of HPCBs leaving model by migration of Secondary Consumers]

H_Migrate_1 = (HPCBs_SC/SC_Res_Time)

[FLOW-g/y of LPCBs leaving model by migration of Tertiary Consumers]

L_Migrate_2 = (LPCBs_TC/TC_Res_Time)

[FLOW-g/y of HPCBs leaving model by migration of Tertiary Consumers]

H_Migrate_2 = (HPCBs_TC/TC_Res_Time)

[STOCK-Total grams of PCBs that have left model by physical processes from Coastal (Shallow) Water]

S_Gone(t) = S_Gone(t - dt) + (H_Disperion_S + L_Disperion_S + H_Eroded_S + L_Eroded_S) * dt

INIT S_Gone = 0

Inflows:

[FLOW-g/y of HPCBs leaving model by current from Shallow Water]

H_Disperion_S = Area_Water_Column_S*H_Conc_S_Water*S_Water_Velocity

[FLOW-g/y of LPCBs leaving model by current from Shallow Water]

L_Disperion_S = Area_Water_Column_S*L_Conc_S_Water*S_Water_Velocity

[FLOW-g/y of HPCBs leaving model by sediment erosion from Shallow Sediment]

H_Eroded_S = Width_CWC*(1/Den_Sed)*H_Conc_S_Sediment*V_Coast_Sed

[FLOW-g/y of LPCBs leaving model by sediment erosion from Shallow Sediment]

L_Eroded_S = Width_CWC*(1/Den_Sed)*L_Conc__S_Sediment*V_Coast_Sed

[STOCK-mg of C per m^2 of Tertiary Consumer biomass]

TC(t) = TC(t - dt) + (TC_Births - TC_Deaths) * dt

INIT TC = 8.1

Inflows:

[FLOW-mg/y of Tertiary Consumers Born]

TC_Births = TC*TC_Birth_Frac

Outflows:

[Flow-mg/y of Secondary Consumers Dying]

TC_Deaths = TC*TC_Death_Frac

[VALUE-$meter^2$ of coastal water]

Area = 92600*46300

[VALUE-$meter^2$ of deep coastal water column]

Area_Water_Column_D = 200*20

[VALUE-$meter^2$ of shallow coastal water column]

Area_Water_Column_S = 18.52E6

[VALUE-density of sediment in kg/m^3]

Den_Sed = 1555

[VALUE-density of sea water in kg/m^3]

Den_Water = 1025

[VALUE-deep water velocity in m/y]

D_Water_Velocity = 1576800

[VALUE-acceleration due to gravity in m/y^2]

g = 9.753E15

[VALUE-HPCB uptake efficiency]
Gam_H = .45

[VALUE-LPCB uptake efficiency]
Gam_L = .55

[VALUE-HPCB Octanol-Water partition coefficient]
HKow = 10^7

[VALUE-HPCB Sediment-Water partition coefficient]
HKsw = 10^4

[VALUE-HPCB Concentration in Deep Sediment in g/m^3]
H_Conc_D_Sediment = HPCBs_D_Sediment/Vol_D_Sediment

[VALUE-HPCB Concentration in Deep Water in g/m^3]
H_Conc_D_Water = HPCBs_D_Water/Vol_D_Water

[VALUE-HPCB Concentration in Primary Consumers in g/m^3]
H_Conc_PC = HPCBs_PC/PC_Volume

[VALUE-HPCB Concentration in Secondary Consumers in g/m^3]
H_Conc_SC = HPCBs_SC/SC_Volume

[VALUE-HPCB Concentration in Shallow Sediment in g/m^3]
H_Conc_S_Sediment = HPCBs_S_Sediment/Vol_S_Sediment

[VALUE-HPCB Concentration in Shallow Water in g/m^3]
H_Conc_S_Water = HPCBs_S_Water/Vol_S_Water

[VALUE-HPCB Concentration in Tertiary Consumers in g/m^3]
H_Conc_TC = HPCBs_TC/TC_Volume

[VALUE-Coastal Water's ability to transport sediment]
K_coast = .603

[VALUE-Deep Water's ability to transport sediment]
K_deep = .6

[VALUE-Upwelling Water's ability to transport sediment]
K__Up = .5797

[VALUE-LPCB Octanol-Water Partition Coefficient]
LKow = 10^6

[VALUE-LPCB Sediment-Water Partition Coefficient]
LKsw = 10^4

[VALUE-LPCB Concentration in Deep Sediment in g/m^3]
L_Conc_D_Sediment = LPCBs_D_Sediment/Vol_D_Sediment

[VALUE-LPCB Concentration in Deep Water in g/m^3]
L_Conc_D_Water = LPCBs_D_Water/Vol_D_Water

[VALUE-LPCB Concentration in Primary Consumers in g/m^3]
L_Conc_PC = LPCBs_PC/PC_Volume

[VALUE-LPCB Concentration in Secondary Consumers in g/m^3]
L_Conc_SC = LPCBs_SC/SC_Volume

[VALUE-LPCB Concentration in Shallow Water in g/m^3]
L_Conc_S_Water = LPCBs__S_Water/Vol_S_Water

[VALUE-LPCB Concentration in Tertiary Consumers in g/m^3]
L_Conc_TC = LPCBs_TC/TC_Volume

[VALUE-LPCB Concentration in Shallow (Coastal) Sedimenet in g/m^3]
L_Conc__S_Sediment = LPCBs_S_Sediment/Vol_S_Sediment

[VALUE-Coastal Water sediment transport ability-fluid power]
Omega_C = (3E-3)*Den_Water*(S_Water_Velocity^3)

[VALUE-Deep Water sediment transport ability-fluid power]
Omega_D = (3E-3)*Den_Water*(D_Water_Velocity^3)

[VALUE-Upwelling Water sediment transport ability-fluid power]
Omega_Up = (3E-3)*Den_Water*(Upwell_Velocity^3)

[VALUE-Primary Consumer Birth Fraction]
PC_Birth_Frav = 6

[VALUE-mg/y of Primary Consumers eaten by Secondary Consumers]
PC_Eaten = (.2*SC*PC_killed_per_SC)*Area*Spec_Vol_C

[VALUE-Total mg of Primary Consumers]
PC_Mass = PC*Area

[VALUE-mg/y of Primary Consumers dying from starvation]
PC_Starve = (.8*PC*PC_Death_Frac)*Area*Spec_Vol_C

[VALUE-volume of Primary Consumers in m^3]
PC_Volume = PC_Mass*Spec_Vol_C

[VALUE-Primary Producer Birth Fraction]
PP_Birth_Frac = 62.5*Sun_Light

[VALUE-Total mg of Primary Producers]
PP_Mass = PP*Area

[VALUE-volume of Primary Producers in m^3]
PP_Volume = PP_Mass*Spec_Vol_C

[VALUE-Secondary Consumer Birth Fraction]
SC_Birth_Frac = .2

[VALUE-Secondary Consumer PCB Concentration in Femtograms per $meter^3$]
SC_Data = Total_Conc_SC*1E15

[VALUE-mg/y of Secondary Consumers eaten by Tertiary Consumers]
SC_Eaten = (.2*SC_killed_per_TC*TC)*Area*Spec_Vol_C

[VALUE-mg of Secondary Consumers in model]
SC_Mass = SC*Area

[VALUE-Residence Time of Secondary Consumers in model]
SC_Res_Time = IF(Storm=0)THEN(.2)ELSE(.05)

[VALUE-mg/y of Secondary Consumers starving to death]
SC_Starve = (.8*SC*SC_Death_Frac)*Area*Spec_Vol_C

[VALUE-volume of Secondary Consumers in m^3]
SC_Volume = SC_Mass*Spec_Vol_C

[VALUE-Season, used to control probability of storms]
Season = SINWAVE(1,1)

[VALUE-Specific Volume of C in m^3 per mg]
Spec_Vol_C = (1/(2.26E9))

[VALUE-Occurence of Storm with 1 being a storm and 0 not being a storm]
Storm = IF(RANDOM(0,1,1)<Strom_Prob)THEN(1)ELSE(0)

[VALUE-Probability of a storm occuring varying with season]
Strom_Prob = IF(Season<-.707)THEN(.12)ELSE(.01)

[VALUE-Sunlight varying with seaon--affects Primary Producer Productivity]
Sun_Light = 1+SINWAVE(.15,1)

[VALUE-Shallow(Coastal) Water current in m/y]
S_Water_Velocity = IF(Storm=0)THEN(8000000)ELSE(80000000)

[VALUE-Tertiary Consumer Birth Fraction]
TC_Birth_Frac = .05

[VALUE-Tertiary Consumer PCB Concentration in Femtograms per meter^3]
TC_Data = Total_Conc_TC*1E15

[VALUE-mg of Tertiary Consumers in model]
TC_Mass = TC*Area

[VALUE-Residence Time of Tertiary Consumers in model in years]
TC_Res_Time = IF(Storm=0)THEN(.2)ELSE(.05)

[VALUE-mg/y of Tertiary Consumers starving to death]
TC_Starve = (TC_Deaths)*Area*Spec_Vol_C

[VALUE-volume of Tertiary Consumers in m^3]
TC_Volume = TC_Mass*Spec_Vol_C

[VALUE-Total PCB concentration of Primary Consumers in grams per meter^3]
Total_Conc_PC = Total_PC/PC_Volume

[VALUE-Total PCB concentration of Secondary Consumers in grams per meter^3]
Total_Conc_SC = Total_SC/SC_Volume

[VALUE-Total PCB concentration of Tertiary Consumers in grams per meter^3]
Total_Conc_TC = Total_TC/TC_Volume

[VALUE-Total grams of PCBs in Primary Consumers]
Total_PC = HPCBs_PC+LPCBs_PC

[VALUE-Total mass in grams of PCBs in model used for conservation of mass]
Total_PCBs =
Completely_Degraded+D_Gone+HPCBs_D_Sediment+HPCBs_D_Water+HPCBs_in_Wreck+HPCBs_PC
+HPCBs_PP+HPCBs_SC+HPCBs_S_Sediment+HPCBs_S_Water+HPCBs_TC+LPCBs_D_Sediment+LP
CBs_D_Water+LPCBs_in_Wreck+LPCBs_PC+LPCBs_PP+LPCBs_SC+LPCBs_S_Sediment+LPCBs_TC
+LPCBs__S_Water+Swam_Away+S_Gone

[VALUE-Total grams of PCBs in Secondary Consumers]
Total_SC = HPCBs_SC+LPCBs_SC

[VALUE-Total grams of PCBs in Shallow(Coastal) Sediment]
Total_S_Sediment = LPCBs_S_Sediment+HPCBs_S_Sediment

[VALUE-Total grams of PCBs in Shallow(Coastal) Sediment]
Total_S_Water = HPCBs_S_Water+LPCBs__S_Water

[VALUE-Total grams of PCBs in Tertiary Consumers]
Total_TC = HPCBs_TC+LPCBs_TC

[VALUE-Total grams of PCBs remaining in wreck]
Total_Wreck = HPCBs_in_Wreck+LPCBs_in_Wreck

[VALUE-Vertical Velocity of Upwelling Water]
Upwell_Velocity = IF(Storm=1)THEN(365)ELSE(182.5)

[VALUE-Volume of Deep Sediment in meter^3]
Vol_D_Sediment = 3.14159*(100^2)*.1

[VALUE-Volume of Deep Water in meter^3]
Vol_D_Water = 3.14159*(100^2)*20

[VALUE-Volume of Shallow(Coastal) Sediment in meter^3]
Vol_S_Sediment = 46300*92600*.1

[VALUE-Volume of Shallow(Coastal) Water in meter^3]
Vol_S_Water = 428738E6

[VALUE-Velocity of the Coastal Sediment in Kgs/m/y]
V_Coast_Sed = (K_coast*Omega_C)/(g*((Den_Sed-Den_Water)/Den_Sed))

[VALUE-Velocity of the Deep Sediment in Kgs/m/y]
V_Deep_Sed = (K_deep*Omega_D)/(g*((Den_Sed-Den_Water)/Den_Sed))

[VALUE-Velocity of the Upwelling Sediment in Kgs/m/y]
V_Up_Sed = (K__Up*Omega_Up)/(g*((Den_Sed-Den_Water)/Den_Sed))

[VALUE-Width of the Coastal Water Column in meters]
Width_CWC = 92600

[VALUE-Width of the Deep Water Column in meters]
Width_DWC = 200

[VALUE-Primary Consumer Death Fraction]
PC_Death_Frac = GRAPH(PP)
(7.00, 9.85), (7.60, 9.70), (8.20, 9.41), (8.80, 8.52), (9.40, 6.93), (10.00, 6.00), (10.6, 5.40), (11.2, 4.80), (11.8, 4.51), (12.4, 4.26), (13.0, 4.00)

[VALUE-mg of Primary Consumers killed per mg of Secondary Consumers a year]
PC_killed_per_SC = GRAPH(PC)
(5.00, 0.18), (6.50, 0.26), (8.00, 0.48), (9.50, 0.82), (11.0, 1.38), (12.5, 2.22), (14.0, 2.76), (15.5, 3.14), (17.0, 3.40), (18.5, 3.62), (20.0, 3.74)

[VALUE-mg of Primary Producers killed per mg of Primary Consumers a year]
PP_killed_per_PC = GRAPH(PP)
(5.00, 4.13), (6.00, 5.25), (7.00, 7.88), (8.00, 15.4), (9.00, 29.6), (10.0, 50.0), (11.0, 66.4), (12.0, 75.2), (13.0, 78.8), (14.0, 81.9), (15.0, 83.7)

[VALUE-Secondary Consumer Death Fraction]

SC_Death_Frac = GRAPH(PC)
(5.00, 0.365), (6.50, 0.36), (8.00, 0.335), (9.50, 0.283), (11.0, 0.239), (12.5, 0.2), (14.0, 0.165), (15.5, 0.138), (17.0, 0.12), (18.5, 0.108), (20.0, 0.1)

[VALUE-mg of Secondary Consumers killed per mg of Tertiary Consumers a year]

SC_killed_per_TC = GRAPH(SC)
(19.0, 0.19), (22.0, 0.23), (24.9, 0.29), (27.9, 0.4), (30.8, 0.56), (33.8, 0.833), (36.7, 1.16), (39.7, 1.34), (42.6, 1.48), (45.6, 1.54), (48.5, 1.56)

[VALUE-Tertiary Consumer Death Fraction]

TC_Death_Frac = GRAPH(SC)
(19.0, 0.181), (22.0, 0.176), (24.9, 0.161), (27.9, 0.119), (30.8, 0.0674), (33.8, 0.05), (36.7, 0.044), (39.7, 0.038), (42.6, 0.035), (45.6, 0.034), (48.5, 0.033)

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Vita

Capt Charles N. Wendt was born on 7 May 1969 in Wilmington, North Carolina. The son of a career Air Force Officer, he grew up in many places including time overseas. In 1987 he was awarded an ROTC scholarship. He graduated with a Bachelor of Science Degree in Electrical Engineering in 1992 from Ohio University, Athens, Ohio and received his commission on 13 June of the same year.

His first assignment was at Minot AFB as a civil engineering officer in January 1993. While assigned there he deployed to Dhahran, Kingdom of Saudi Arabia, in support of Operations DESERT STORM, SOUTHERN WATCH, and VIGILANT WARRIOR from September to December 1994. In May 1995, he entered the School of Engineering, Air Force Institute of Technology.

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13. ABSTRACT *(Maximum 200 words)*

In the past, the U.S. Navy has routinely conducted SINKing EXercises (SINKEX) for training, weapon effectiveness tests, and economic disposal of aging assets. Recent concern over polychlorinated biphenyl (PCB) chemicals aboard such target vessels has resulted in a suspension of SINKEX. The U.S. Navy has approximately 200 vessels currently requiring such disposal. Environmental legislation and health concerns preclude selling such vessels to foreign governments or scrapping.

This work attempted to model the fate and transport of these PCBs by examining their transport to coastal water and their accumulation in the marine food chain. The model includes biodegradation, upwelling, partitioning of PCBs to sediment, sediment transport, bioaccumulation, biomagnification, and biological migration. Seasonal fluctuations in marine biomass and storm activity and how this affects PCB concentrations is also examined. The model uses a four trophic level approach for the marine food chain. A total of 55 runs, each simulating a 50 year period, were conducted.

Model output and subsequent sensitivity analysis of parameters indicate that the potential for adverse impact to the marine ecosystem is minimal.

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